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ON THE
PROPERTIES OF SEA-ICE

ACADEMICAL DISSERTATION

BY

FINN MALMGREN

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A/S JOHN GRIEGS BOKTRYKKERI, BERGEN

On the Properties of Sea-Ice

Academical Dissertation

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ON THE PROPERTIES OF SEA-ICE.

BY *FINN MALMGREN.*

I. Introduction.

This paper is based on investigations carried out during the Norwegian expedition to the Polar Sea in 1922—1925.

The expedition left Seattle on board its ship, the "Maud", in the summer of 1922 and steered through Bering Strait into the Polar Sea. We intended to penetrate as far north as possible, and then let the ship freeze in among the drifting floes. It was hoped that the ice during the next three or four years would carry the ship across the central parts of the Polar Sea to the opening between Greenland and Spitzbergen. Thus we hoped that the "Maud"-Expedition, with its better scientific equipment, would be enabled to repeat the very successful drift of the "Fram".

These anticipations were not realized, however, as the ice conditions were very unfavourable. When the cold set in, making all further navigation impossible, in the autumn of 1922, the vessel had reached only $72^{\circ} 20' \text{ N. L.}$ and $175^{\circ} 25' \text{ W. Gr.}$ There we froze in among the floes and were held fast by the ice for nearly two years, following the ice in all its movements. During this period the "Maud" drifted chiefly towards WNW, to about $76^{\circ} 30' \text{ N. L.}$ and $143^{\circ} 15' \text{ E. Gr.}$ This drift being very unsatisfactory, Captain Amundsen in the interests of safety recalled the expedition in the spring of 1924.

During the summer of 1924, therefore, an attempt was made to return through Bering Strait; but although the ship succeeded in getting out of the drift ice and in covering some of her passage home, she was forced by new ice difficulties to winter at the "Bear Islands" near the north coast of Siberia. In the following summer the ice difficulties were less, and the "Maud" was able to return to civilization.

From what has been said it will be seen that the "Maud"-Expedition spent about three years in the frozen Polar Sea. All around the ship there extended endless expanses of different kinds of sea-ice. Under these circumstances we naturally devoted much of our time to the study of ice, all the more as the knowledge of sea-ice in many respects is imperfect.

At the suggestion of Professor H. U. Sverdrup, in charge of the scientific work of the expedition, I therefore undertook an investigation of the sea-ice, its specific gravity, content of salt, thermal characteristics etc. In connection with the publication of these researches, Sverdrup also asked me to publish and discuss some regular observations, ice temperatures etc., that had been taken during the expedition, chiefly by himself. These observations are edited in the present paper, together with my own investigations.

During the whole time we spent on board I was greatly helped in my work by Prof. Sverdrup. I take the present opportunity of expressing my most sincere gratitude for the great interest he took in my work and for the valuable assistance with which he facilitated my investigations. Later on, when finishing off my paper at Upsala in Sweden, I derived the most valuable help from Prof. F. Åkerblom, the Director of the Meteorological Institute at Upsala. I am specially indebted to Prof. Åkerblom for his guidance to the literature of the Arctic regions, of which his knowledge appears to be inexhaustible.

II. The salt in sea-ice.

Definition of the Salinity of the Ice.

The chief difference between sea-ice and freshwater-ice consists in the occurrence of salt in the former. Thus if we melt a piece of sea-ice and evaporate the resulting water, there will be found a solid sediment of different salts, which were formerly found in the ice.

We shall define the *Salinity* (S) of a piece of sea-ice as *the weight in grams of all the solid matters obtained on evaporating the water resulting from the melting of 1000 grams of sea-ice*. In doing this we must, in accordance with the definition of the salinity of sea water given by S. P. L. Sørensen and Martin Knudsen ¹⁾, substitute an equivalent quantity of chlorine for the quantity of bromine, convert all carbonates into oxides, and heat until all organic matter is burnt off.

There are a few very important differences between the salt in the water and in the ice, which must be mentioned at once, although we shall have to study them more closely later on. The salinity of sea-water is a very conservative attribute, the water having for a long time the same salinity, which only slowly changes — for instance through precipitation, evaporation, or through mixing with another kind of water. The salinity of ice, on the other hand, may change very rapidly. Furthermore the salt in sea-water always consists of the same constituents, which are practically always found in the same proportions. The salt in sea-ice may have a more variable composition, yet, as will be shown later on, not in so high degree as previously has been stated by many authors (O. Pettersson a. o.).

The most characteristic dissimilarity, however, is connected with the different ways in which the salt exists in water and in ice. Sea-water is a homogeneous solution of salt; and consequently S will be the same however small an amount of water is chosen. This is not the case with ice. Here the salt is found as a concentrated brine, filling very small cavities distributed throughout the pure ice (and at low temperatures also as small crystals, occurring all through the interior of the ice).

S is a *mean value* of the salinity in the piece of sea-ice when melted. If this mean value is to have any real significance, the weight of the sample used for the determination of S must be so great that occasional variations in the percentage of salt in the particles of ice have no influence on S ; the resultant S must be *representative* of the ice investigated. I have tried to determine how small samples of ice can be taken in order to get a good value for S . From the interior of a big block of ice four samples were taken close to one another, each sample weighing about

¹⁾ Kongl. Danske Videnskabs Selsk. Skrifter, Bd. 12, 1902, p. 16; Wissenschaftliche Meeresuntersuchungen, herausg. von der Komm. z. Unters. d. Deutschen Meere in Kiel, Bd. 6, Kiel 1902, p. 139.

50 grams. The pieces were melted and the percentage of chlorine was determined through titration, giving the following values:

$$Cl = 1.98, 1.97, 1.96 \text{ and } 2.02 \text{ ‰}$$

The amount of chlorine being constant, S also must be constant, as there is no reason why the composition of salt should vary in the middle of a big block of ice. Thus it will be seen that for *that* sea-ice a sample weighing 50 grams was sufficient to get a representative value for S if the ratio chlorine to total amount of salt were known. It is possible that still smaller pieces of ice would have given the same value for S , but the question could not be decided; in fact, the chlorine titration of smaller quantities of melting-water with such a low salinity is rather difficult.

Influence of Freezing Velocity and Age on the Salinity of Sea-Ice.

After these few words on the definition of the salinity of ice we shall study some questions in connection with the occurrence of salt in sea-ice.

The existence of salt in the ice is explained by considering what happens during the process of freezing at the boundary between ice and water, a process that previously has been studied by many Arctic explorers. First there is formed a network of fine elongated crystal prisms which extend downwards into the water from the underside of the ice. Later on also the sea-water between these crystals starts freezing. In freezing the sea-water is separated into pure ice and a concentrated brine which through its higher specific gravity tries to soak down through the porous pulp of ice crystals. But as the latter grows thicker and thicker, the running off of the brine is stopped and a part of the salt is retained by the ice.

From the above it is seen that the more quickly the freezing takes place, the saltier becomes the ice which is formed, for the brine has less time to run off. This fact is illustrated by the following determinations of salinity, based on different kinds of new-ice collected during the winter of 1923—1924 in the Polar Sea. The numbers refer to ice-floes, which were frozen out of sea-water with the same salinity and to about the same thickness (20 cm.). As the wind conditions and cloudiness at the time of freezing were about the same, the only difference lay in the temperature. Under such conditions, of course, freezing takes place most rapidly at the lowest temperature. As was to be expected, the salinity of the ice formed increases with falling temperature.

Table 1.

Temperature ¹⁾	Salinity computed	
	by Cl -titration of the melting-water ‰	by determination of the spec. grav. of the melting-water ‰
— 16°	5.64	—
— 28°	8.01	7.97
— 30°	8.77	8.67
— 40°	10.16	10.22

The fact that the salinity is dependent on the velocity with which the formation of ice takes place is also illustrated by the following table, which shows that the

¹⁾ Centigrade. All temperatures in this paper are given in the centigrade temperature scale.

salinity is a function of the depth reckoned from the surface of the ice. The ice investigated was a new-ice area, which began to freeze in November 1924. The samples were taken in April, 1925, and the salinities were determined by chlorine titration.

Table 2.

Distance from the surface of the ice (cm.)..	0	6	13	25	45	82	95
Salinity (pro mille)	6.74	5.28	5.31	3.84	4.37	3.48	3.17

This table shows that the salinity of the ice decreases as we go down from the surface, in accordance with the slower rate of freezing at the greater depths. The low salinity at the depth of 25 cm. may have been caused by the occurrence of a couple of warm days shortly after the ice began to form.

Similar results were obtained by K. Weyprecht¹⁾ during his drift with the "Tegetthoff". The ice investigated was a piece of new ice frozen at -33° . The thickness of the ice was 19 cm. The first 5 cm. showed a salinity of 25 ‰; the next 9 cm. 13 ‰, and the last 5 cm. 12 ‰. The samples were taken only 60 hours after the freezing had begun, which explains the great amount of salt. The "salinity" for the uppermost 5 cm. of ice included some solid "salt" lying on the surface of the ice. In the Polar Sea such solid "salt" always occurs on the surface of the ice, when open water freezes at very low temperatures. The "salt" may form so freely that the young ice looks like a lawn on a morning with hoar-frost. According to Weyprecht, however, the "salt" is not pure: it consists of fine needles of ice bearing small salt crystals at their points.

The salinity of a piece of sea-ice does not depend solely on the rate of freezing. Another very important fact is the age of the ice: *The older the ice, the less salt it contains.*

Especially during the summer, but also in spring, the ice slowly loses a great deal of its salt. As the temperature increases, the salt brine between the ice crystals absorbs water and tries to find its way out of the ice, which is now more porous. How porous the ice really is in summertime is proved by an incident that happened during the "Maud" expedition. On May 30, 1924 we wanted to pick up one of the ice thermometers, and for that reason a hole was dug in the ice about one meter deep and about half a meter square. There was no water on the ice in the neighbourhood, and yet on the following day the hole was entirely filled with a fluid, which, on closer investigation, proved to be a brine with a much higher salinity than the sea-ice itself. The salinity of the brine was 51 ‰, that of the sea-water 28 ‰ and that of the ice only 3 ‰, all computed by chlorine titration. This brine had certainly originated from the interior of the sea-ice around the hole and had during a single day trickled from the walls in such large quantities as to fill the hole.

The downward movement of the brine of the sea-ice in summertime often has the result that the highest pieces of screwed-up ice, formed by ice pressures, become entirely fresh, so that later they can be used for the production of drinking water. Moreover the pools of melting-water that in summer are formed on big old-ice floes — i. e. sea-ice which has existed at least one whole summer — may be quite free of salt, as has often been observed by explorers and seal-hunters. The best drinking water obtainable during winter, for that matter, is produced by the melting of ice from such pools.

¹⁾ Weyprecht K.: Die Metamorphosen des Polareises. Wien 1879.

The Composition of the Salt in Sea-Ice

Sea-ice is formed by the freezing of sea-water; that means, the salts existing in the sea-ice must previously have been in the sea-water. But the questions now arise: Are all the salts found in the water also to be found in the ice, and are the percentages of the different salts the same in both cases?

Before we enter into these questions, we shall first see what happens when a dilute solution of salt is freezing. To start with, we choose a dilute solution of only *one* salt, which we expose to gradually sinking temperatures, starting at the freezing point. At first only pure ice is formed, and consequently the concentration of the solution is increased. At every temperature the solution has a fixed concentration, independent of the original percentage of salt. If the temperature is still further lowered, more and more ice is formed until, at a certain temperature, the eutectic, solid salt also begins to precipitate. On further loss of heat the temperature keeps constant until the whole system has solidified into a uniform conglomerate, the cryohydrate. Later the temperature of the system begins to fall again.

If we have a dilute solution of more than one salt, the conditions become more complex. In this case it can be shown that the eutectic temperature of the different salts is lowered.¹⁾ A solution of pure Na_2SO_4 , for instance, has its eutectic temperature at -0.7° ²⁾; but in the freezing of sea-water in which many other salts are present Na_2SO_4 does not begin to precipitate until -8.2° . Moreover the precipitation of a particular salt does not take place entirely at a certain temperature, but gradually over a whole range of temperatures.

In sea-water, with its numerous components, the conditions are very complicated. The only thing that facilitates the study of its freezing is that all kinds of sea-water have the same salt-composition. Also all kinds of sea-water are so dilute solutions of salts that *ice* is always the first substance to freeze out. The consequence of this is that, whatever the salinity of the sea-water may be, the progress of freezing will be almost the same: *At every fixed temperature the concentration and the composition of the brine will be very nearly the same for all kinds of sea-waters, irrespective of their original salinities.* The only difference will occur in the proportion of pure ice to brine that is to be found in the samples.

Let us take 1 gram of sea-water with the salinity S and expose the system to lower and lower temperatures. The freezing sets in at τ_s° . As we shall see later on, only pure ice will be formed until we reach a temperature of -8.2° . If τ is a temperature between τ_s and -8.2° , there exists at that temperature a_τ grams of brine and $(1 - a_\tau)$ grams of pure ice. If the salinity of the brine is S_τ we have

$$a_\tau \cdot S_\tau = S$$

One gram of another sea water with a salinity S' would have given a similar equation:

$$a'_\tau \cdot S'_\tau = S',$$

where a'_τ and S'_τ respectively are the weight and the salinity of the brine at τ° . As $S'_\tau = S_\tau$ we thus get:

$$\frac{S}{S'} = \frac{a_\tau}{a'_\tau} \text{ or } \frac{S}{a_\tau} = \frac{S'}{a'_\tau} = C,$$

¹⁾ See, for instance, Schreinemaker's article in Zeitschr. f. Ph. Ch. XII, 1893 p. 73.

²⁾ W. E. Ringer: Ueber die Veraenderungen in der Zusammensetzung des Meereswassersalzes beim Ausfrieren. Verhandelingen uit het Rijksinstituut voor het Onderzoek der Zee. Eerste del, Helder 1906.

where C is a constant. This means that *the quantity of brine per gram is proportional to the salinity*.

At a temperature a little below -8.2° solid salt in both systems is also precipitated, with a quantity that is *proportional* to the weight of the brine at -8.2° ($a_{-8.2}$ and $a'_{-8.2}$) — the concentration of the brine at -8.2° in both systems being the same. As the amount of separated salt will always be proportional to the weight of the existing brine, we see that the concentration of the brine at any temperature will continue to be the same for both the systems. Thus even at low temperatures the law found above holds good.

We have before mentioned that no solid salt is precipitated until we reach a temperature of -8.2° . This temperature was determined by W. E. Ringer¹⁾ who has made a detailed investigation of the changes in composition of sea-water caused by freezing. He found that the freezing was a selective process²⁾. We will here give a short account of his experiments.

Ringer made his experiments with a sea-water whose salinity was 35.05 ‰. This water began to freeze at -1.91° . Down to -8.2° only pure ice was formed, but at that temperature Na_2SO_4 began to precipitate. The solidification of the Na_2SO_4 took place so freely that at -20° only one tenth of the original amount of SO_3 was left in the brine. On the other hand, the brine retained all chlorine, which did not begin to precipitate as solid NaCl until at a temperature of -23° .

The composition of the system down to -30° is shown in the following table (Ringer p. 38).

Table 3.

Temperature Centigrade	Liquid ‰	Solid NaCl ‰	Solid Na_2SO_4 ‰	Pure Ice ‰
— 5	429.5	—	—	570.5
— 8.2	281.5	—	—	718.5
— 10	234.0	—	1.84	764.2
— 15	186.1	—	3.09	810.8
— 20	147.9	—	3.58	848.5
— 23	134.6	—	3.68	861.7
— 30	43.95	20.23	3.95	931.9

We see from this table that the formation of Na_2SO_4 takes place chiefly between -8.2° and -15° , while solid NaCl does not begin to form until temperatures below -23° .

It is on the basis of these facts that Pettersson and Ringer assume a selective character of the freezing process in nature. According to them the sea-water in the Polar Sea loses SO_3 through the freezing in of Na_2SO_4 into the ice, thus showing a surplus of Cl , while the water in the North Atlantic receives a contribution of Na_2SO_4 , thus showing a surplus of SO_3 .

Pettersson and Ringer argue in the following way. At the low winter temperatures in the Arctic SO_3 is separated as solid Na_2SO_4 in the sea-ice, while Cl is still left in the brine existing between the ice particles. Gradually part of this brine finds its way downward and adds Cl to the sea-water. The amount of SO_3 , on the con-

¹⁾ W. E. Ringer: Ueber die Veraenderungen, etc.

²⁾ Previously proved by Pettersson.

trary, is taken away by the drifting ice and follows the floes out through the strait between Greenland and Spitzbergen. The melting of the ice takes place in the North Atlantic, and not till then does the SO_3 again join the sea-water, thus decreasing its percentage of chlorine.

During the "Maud"-Expedition there were good opportunities to check this theory. But our measurements on board showed that in the Polar Sea no *such selective freezing process takes place on a big scale*. The same was found later after our return to civilisation. Ordinary sea-water as well as water derived from melted ice were brought home and investigated in Bergen. The samples both showed almost the same ratio SO_3 to Cl , the ratio being 0.1179 for the melting-water and 0.1176 for the ordinary sea-water. This remarkable fact will be discussed more fully in connection with the publication of the oceanographical work of the Expedition.

But even without these facts it is difficult to believe that a selective freezing process of the kind described above can take place on a large scale: too little notice is taken of the temperature. We have to bear in mind the fact that the salinity of the chief part of the newly frozen ice is not very great, as the ice is formed at rather high temperatures, at which the rate of the freezing process is slow. This is due to the fact that, as a rule, the new-ice in the Polar Ocean is formed on the underside of the old-ice floes, where the temperature is high. Only in some parts of the sea, especially in the region between 73° N.L. and the Chukotsk and the Alaskan peninsulas ice is formed on a large scale at the water surface; but this takes place in the autumn, before the temperature is really low. Now the experience from the "Maud" has shown that sea-ice with *low salinity* is able to keep a constant salinity for a very long time unless the temperature goes up to more than 4 or 5 degrees below zero. At fairly great depths, for instance, old-ice floes may show almost the same salinity in two following years. Hence we can expect that the trickling down of the brine in sea-ice floes with low salinities ($< 5\text{‰}$) is very slight at temperatures below -8.2° . At higher temperatures the brine may trickle down, for instance in summer time, when the ice is exposed to the sun. But this has no influence on the composition of the salt in the sea, as in that case the brine also contains the whole amount of Na_2SO_4 .

After what has been said it must be evident that we cannot expect to find any very marked difference in the composition of the sea-water, even in places where the ice melts on a big scale. This is in accordance with the measurements made by Hamberg¹⁾ and Schmelck²⁾ who both found that the ratio SO_3 to Cl is practically normal in the melting zones.

The Salinity in different Kinds of Sea-Ice.

Determinations carried out during the Expedition.

The salinity of the sea-ice was determined by investigating its melting-water, both the amount of chlorine and the specific gravity being measured. The chlorine was determined by titration with a solution of $AgNO_3$, the strength of which was fixed with standard sea-water from the International Laboratory, Copenhagen. The specific gravity was measured with Nansen's hydrometer of total immersion³⁾.

The salinity (S) of the sea-ice was computed from both of these readings by means of Knudsen's Tables⁴⁾. There was only a slight difference between the salinity derived

¹⁾ Bih. K. Sv. Vet. Akad. Handl. Stockholm 1885. Bd. 10 Nr. 13. p. 14.

²⁾ Norske Nordhavs Exp. Chemi. Kristiania 1882. p. 13.

³⁾ Scientific Results of the Norwegian North Polar Expedition. Vol. 3. Nr. X. Kristiania 1900. p. 78.

⁴⁾ Hydrographical Tables, edited by Martin Knudsen. Copenhagen and London 1901.

from the chlorine and that derived from the specific gravity, *which shows that the melting-water had the standard composition of a sea-water.*

Of the two values of S , that computed from the specific gravity is the better; and accordingly the value derived from the amount of chlorine is put in parentheses. The error in S , computed from the specific gravity very seldom amounts to more than ± 0.05 ‰. (For fuller information on this point see the oceanographical part of this work, which is to be published shortly).

The Tables 4 and 5 contain the results of the determinations of salinity in sea-ice.

Table 4.

Date and year.	Amount of Cl ‰	σ_0 . (Sp. gravity at 0° from titr. $= s_0$. $s_0 = 1 + \frac{\sigma_0}{1000}$)	σ_{0N} . (Sp. gravity at 0° w. aerom. $= s_{0N}$. $s_{0N} = 1 + \frac{\sigma_{0N}}{1000}$)	Difference ($\sigma_{0N} - \sigma_0$) multiplied by 100.	Salinity from Chlorine ‰	Salinity from spec. grav. ‰	Remarks.
1922							
7.9	1.38	1.96	1.86	— 10	(2.52)	2.39	All samples in this table come from thin new-ice frozen on a hole cleared daily, about 1 meter square. The salinities are not comparable, some of the samples being thinner or holding more adhesive sea-water than the others.
28.9	1.18	1.65	1.54	— 11	(2.15)	2.01	
5.10	3.72	5.38	5.31	— 7	(6.74)	6.65	
12.10	7.24	10.52	10.50	— 2	(13.11)	13.08	
19.10	4.80	6.96	6.86	— 10	(8.69)	8.57	
26.10	5.35	7.76	7.68	— 8	(9.69)	9.59	
2.11	4.89	7.09	7.01	— 8	(8.86)	8.76	
9.11	6.16	8.95	9.02	+ 7	(11.16)	11.25	
16.11	6.34	9.20	9.14	— 6	(11.47)	11.40	
23.11	4.44	6.42	6.36	— 6	(8.04)	7.95	
30.11	5.42	7.86	7.84	— 2	(9.81)	9.79	
14.12	3.66	5.30	5.26	— 4	(6.64)	6.59	
21.12	4.41	6.39	6.33	— 6	(7.99)	7.92	
28.12	4.47	6.48	6.39	— 9	(8.10)	7.99	
1923							
6.1	7.01	10.18	10.21	+ 3	(12.68)	12.72	The sample was wet. The sample was quite dry.
11.1	6.66	9.66	9.62	— 4	(12.04)	12.00	
25.1	6.39	9.28	9.35	+ 7	(11.56)	11.65	
8.2	8.95	13.00	12.94	— 6	(16.18)	16.11	
15.2	2.35	3.38	3.30	— 8	(4.27)	4.17	
22.2	6.30	9.14	9.12	— 2	(11.40)	11.37	
20.9	1.03	1.44	1.32	— 12	(1.89)	1.75	
11.10	1.28	1.81	1.71	— 10	(2.34)	2.21	
29.11	6.75	9.80	9.84	+ 4	(12.22)	12.27	
12.12	7.37	10.70	10.76	+ 6	(13.33)	13.41	
19.12	4.29	6.21	6.14	— 7	(7.77)	7.68	
1924							
22.1	4.19	6.07	6.01	— 6	(7.59)	7.52	

Table 5.

Date of sample	Depth cm.	Amount of Cl ‰	σ_0 . (Sp. gravi- ty at 0° from titr. $= s_0$. $s_0 =$ $1 + \frac{\sigma_0}{1000}$)	σ_{0N} . (Sp. gravi- ty at 0° determ. w. areom. $= s_{0N}$. $s_{0N} =$ $1 + \frac{\sigma_{0N}}{1000}$)	Difference σ_{0N} $-\sigma_0$ multi- plied by 100	Salinity from chlorine ‰	Salinity from spec. grav. ‰	Remarks.
1923 29.1	0	—	—	0.31	—	—	0.4	A) Samples from ice free- zing since 28.9.22. Thick- ness of the ice 130 cm.
"	35	3.11	4.49	4.45	— 4	(5.64)	5.59	
"	52	2.46	3.54	3.44	— 10	(4.47)	4.34	
"	125	4.60	6.66	6.31	— 35	(8.32)	7.89	
1923 19.3	0	—	—	0.19	—	—	0.3	B) Same ice. Thickness now 190 cm. Mean of 2 samples. " " " " Mean of 2 samples.
	30	2.87	4.14	4.06	— 8	(5.21)	5.11	
	51	2.70	3.89	3.82	— 7	(4.90)	4.81	
	80	2.53	3.64	3.61	— 3	(4.60)	4.56	
	112	2.40	3.45	3.41	— 4	(4.36)	4.32	
	165	2.94	4.24	4.18	— 6	(5.34)	5.26	
1925 Begin- ning of April	0	3.72	5.38	—	—	(6.74)	—	C) New-ice, frozen in the be- ginning of November—24
	6	2.91	4.20	—	—	(5.28)	—	
	13	2.93	4.22	—	—	(5.31)	—	
	25	2.11	3.03	—	—	(3.84)	—	
	45	2.40	3.46	—	—	(4.37)	—	
	82	1.91	2.73	—	—	(3.48)	—	
	95	1.74	2.49	—	—	(3.17)	—	
1923 1.2	60	—	—	— 0.07	—	—	0.05	D) Ice frozen 20.8.22 on a pond in an old-ice floe. The pond was open at the bottom, the water in it thus in communication with the sea-water. The upper layers of water in the pond were rather fresh.
	85	1.28	1.81	1.68	— 13	(2.34)	2.18	
	175	3.27	4.73	4.63	— 10	(5.93)	5.82	
1923 4.10	0	0.35	0.44	0.36	— 8	(0.66)	0.55	E) New-ice, frozen on big pond. Thickness 40 cm.
	30	0.90	1.25	1.16	— 9	(1.65)	1.55	
1924 4. 7	0	—	—	— 0.10	—	—	0.0	F) Samples from the old-ice floe where our ice-thermo- meters were placed. The ice now melting.
	60	—	—	0.39	—	—	0.5	
	70	0.62	0.84	—	—	(1.14)	—	
1924 5.3	3	6.79	9.86	9.81	— 5	(12.29)	12.23	G) Screwed-up new-ice, 7 cm. thick, frozen at -38° .
1924 5.2	3	8.06	11.71	11.71	0	(14.59)	14.59	H) Screwed-up new-ice 5,5 cm. thick, frozen at very low temperature.

Table 4 contains new-ice samples, taken in connection with the oceanographical series. The samples originated, as a rule, from a hole in the ice 1 m. square, which was kept open the whole year, the ice being removed from its surface every morning. The salinities are not comparable, some of the samples being thicker than the others. Also some of the samples were made wet by adhesive sea-water, while others were often quite dry, having been placed in the open air for a couple of hours to run off before testing.

The most interesting fact in connection with Table 4 is the composition of the ice. The table shows that the specific gravity, as computed from the amount of chlorine is *higher* as a rule, than the specific gravity as determined by the hydrometer. The mean difference is 0.000045 ($\sigma_{0N} - \sigma_0 = -0.045$). This means that there must be a slightly higher percentage of chlorine in sea-ice than in a sea-water of standard composition. Hence the salinities computed from the chlorine are too large, being 0.055 ‰ larger, on the average, than the values derived from hydrometer measurements.

A curious fact is that the surplus of chlorine grows less as the salinity of the ice increases and finally, at very high salinities, changes into a deficit of chlorine. This is seen from Table 6 where the ice samples are arranged in groups according to the specific gravity of the melting-waters.

Table 6.

Interval of σ_{0N}	Number of samples	σ_{0N}	Mean difference 100 ($\sigma_{0N} - \sigma_0$)
> 9.00	10	10.05	+ 0.7
$9.00 - 5.00$	11	6.47	- 6.6
< 5.00	5	1.95	- 10.2

This indicates that, when freezing takes place very rapidly (at very low temperatures), the salt in the ice will show a deficit in chlorine, as expected by Pettersson and Ringer. Generally, however, the chlorine percentage of the salt in sea-ice will be higher than in the sea-water. *In fact, almost all of the ice samples from the Arctic Sea analysed by us showed a surplus in chlorine* (see also Table 5).

We proceed to Table 5. This table deals with samples of ice taken from different ice-floes in the neighbourhood of the "Maud". The table shows the seasonal changes in salinity at various depths of some different types of sea-ice.

The group of samples marked *C* illustrates the salt conditions in spring found in a new-ice area frozen in the beginning of November. On freezing the sea-water had almost the same salinity in the uppermost eight meters: 21.35 ‰ at surface, 21.40 ‰ at 4 m., and 21.42 ‰ 8 m.

Under such conditions the salinity of the ice shows steadily declining values as we proceed downwards until we approach the water, in the neighbourhood of which the amount of salt increases again. In the interior of the floe the salinity keeps between 3 ‰ and 4 ‰.

Slightly higher values (4–5 ‰) were found in the winter of 1923 in another area of new-ice, frozen on September 28, 1922 (*A* and *B*), the salinity distribution, however, being almost the same (Fig. 1). The only difference is found in the salinity at the surface. In September 1922 there was, in fact, a thin layer of fresh water on the surface of the sea, and this on freezing gave the pure ice on the top.

A similar layer of fresh water also existed when the samples numbered *D* and *E* began to freeze. The *D* samples of ice was formed from a sea-water with the following salinities: 6.33 ‰ at surface, 28.21 ‰ at 5 m. and 31.63 ‰ at 10 m. The corresponding values for the samples *E* were 5.30 ‰ at surface, 28.48 ‰ at 5 m. and 28.46 ‰ at 10 m.

In samples *A* and *B* the thickness of the ice was also measured. In both cases we see that the salinity increases as we approach the underside of the floe. The salt conditions here have not yet become settled; at the high temperature the brine is slowly running down into the water.

The salinities in the upper strata do not alter very much during the winter, but a rapid change takes place when summer sets in. The ice, which is melting on the top, will be partly washed free of salt in its upper layers by the melting-water. Only very little of this water can trickle through the whole of the ice down to the sea-water, as the ice in the deeper layers is too cold. The chief part flows through deep but narrow furrows on the ice surface down to some open hole. Thus a thick ice floe can retain a rather high salinity in the interior all through the summer, but its upper strata will always be washed out. This process sometimes goes so far that the tops of screwed-up ice may become quite fresh. (See *F* in Table 5 and in Fig. 1).

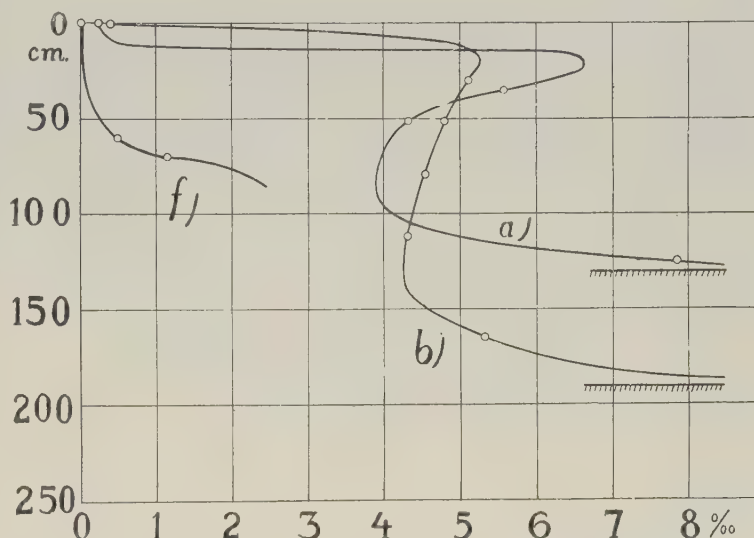


Fig. 1. Observations of salinity of sea-ice in different depths.

The samples marked *G* give us the other limit for the salinity of sea-ice as actually found in nature, giving examples of a very high percentage of salt. Such high salinities are found only in the coldest days of the winter, when thin new-ice is screwed up from the water. The piece of new-ice found on February 5, 1924 is the saltiest analysed on the "Maud"; its salinity was 14.59 ‰.

If we summarize the above observations, we reach the following survey of the salinity of sea-ice:

New-ice which freezes from water with a uniform salinity in the uppermost metres (from October or November till May) has at the surface a salinity which is greater the more rapidly the freezing has taken place, and which in exceptional cases may amount to 15 ‰ immediately after the freezing. Lower down the salinity decreases, rapidly to begin with, but more slowly afterwards. In the central parts of thick new-ice the salinity is found to be between 3 ‰ and 5 ‰. Towards the underside of the ice the salinity again becomes greater, but at a given depth it decreases towards the normal, as the under-side of the ice during the process of freezing becomes more distant from the depth in question.

New-ice that freezes from sea-water with a thin film of fresh water over it (August—October) consists at the top of ice almost free from salt, but at considerable depths it has about the same proportion of salt as the new-ice dealt with above.

The salinity of new-ice decreases with time at all depths (that is to say, at the surface also) during the period immediately after the freezing, but afterwards remains almost constant until May, when the sun begins to affect the topmost layer.

During the summer the new-ice loses a great deal of its original salt in connection with the melting of the surface. This process mainly takes place in the upper layers, where the salt may almost entirely disappear. Yet even lower down the salinity decreases somewhat, so that at considerable depths it is about 2—3 ‰ after the close of the summer.

Moreover we must not imagine that the formation of new-ice on the underside of the ice ceases completely during the summer. During June and July the increment of ice below is relatively great, owing to the fact that melting-water with a high

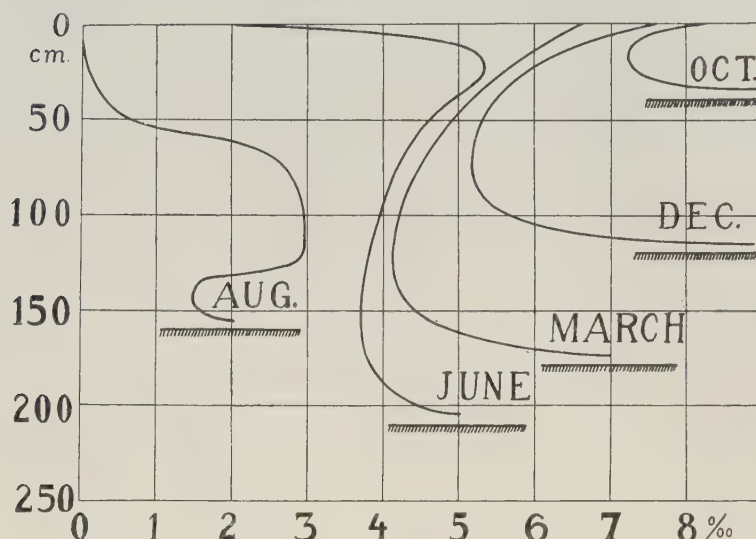


Fig. 2. Schematical representation of salinity of sea-ice as a function of depth in different months.

freezing point runs down through holes in the ice and then freezes, when it encounters the sea-water, which still retains a considerably lower freezing point (about -1.6°)¹). The ice that is thus formed must, however, be very free from salt (a sample of new-ice frozen 5.7.23 at a depth of 2 meters showed a salinity of 0.2 ‰, $\sigma_{0N} = 0.14$).

At the close of the summer the new-ice of the past winter passes over into the class of old-ice, and we get a growth of relatively salt ice again. But the new-ice that is formed under old-ice is never so salt as that which is formed under new-ice. Old-ice has considerably less heat conductivity than new-ice has; and this involves the consequence that the rapidity of freezing on its underside is less than it is in new-ice at a corresponding depth. For the same reason a covering of snow on the ice has a yet greater effect. Ice that is formed under floes that are covered with snow is always *freer from salt* than other ice.

The changes in the new-ice in the course of a year can be graphically followed on the monthly curves in Fig. 2. This shows diagrammatically how ice that is formed in October undergoes gradual change until it acquires the proportion of salt which is shown by the curve for August in the following year. The figure also indicates the thickness of the ice during the different months. The figure is intended only to give a qualitative picture of the course of development and the salinities must not be interpreted as representing the mean values of the salinity during the different months. Our material is far too scanty to enable us to lay down such values.

¹) Also observed by Nansen and others.

III. The specific gravity of sea-ice.

Previous Investigations. Methods of Determinations.

There are many earlier determinations of the specific gravity of sea-ice (s) in Arctic regions. Thus Makaroff¹⁾ has carried out a large number of measurements in the drift-ice north-west of Spitzbergen, and many others have done the same. But both his determinations and those of the others comprise only drift-ice which has been encountered during the summer on the outskirts of the Polar Sea. In consequence of this it has not been possible to give a precise account of the age and life story of the ice-floes investigated. To this must be added the fact that the method for determining the specific gravity has usually been very defective. — Hence we must say that hitherto we have had no very precise knowledge as to the specific gravity of the sea-ice found in the interior of the Polar Sea; in particular, the conditions prevailing during the colder season have been practically unknown.

The method that Makaroff and the others used in determining the specific gravity of sea-ice consisted in measuring the mean height (h) and the mean depth (d) — both reckoned from the surface of the water — of a freely floating ice-floe. If the specific gravity of the water at the temperature in question is $\left(1 + \frac{\sigma_t}{1000}\right)$, then s can be determined from the equation:

$$s = \frac{d}{h + d} \left(1 + \frac{\sigma_t}{1000}\right);$$

It should be observed that s which is determined in this manner is the *mean value* of the specific gravity of the whole floe.

This method labours under two defects. In the first place, it is very difficult to determine d and h with any great accuracy when we are concerned with such irregular bodies as floes of drift-ice. Further the method cannot be used for the determination of the specific gravity of certain sorts of ice *in situ*. A very porous piece of ice, for instance, the top of an old-ice floe at the end of the summer, will thus *increase* its specific gravity when it is laid in water. The water trickles into the holes and increases the value of s , so that it becomes greater than it originally was.

In order to obtain more exact values for s , I made use, on board the "Maud", of another method: I determined the loss of weight which a previously weighed piece of sea-ice underwent when it was immersed in petroleum.

The sample, which consisted of a piece of ice having a weight of some hundred grams, was weighed on deck and was allowed to lie a couple of hours there in order to acquire the temperature of the air. After that it was weighed again in order to make sure that no brine had trickled out. If the weight was still the same, the ice sample was tied round with a piece of wire and suspended on one arm of a balance. Beneath it was placed a mug full of petroleum, in which the piece was immersed in such a way that it hung free. The petroleum was also very nearly air temperature. Care was taken that no air bubbles remained on the outside edges of the ice. The arrangement is shown in Fig. 3.

If a piece of ice weighs G grams in the air and g grams in petroleum with the specific gravity p_t at the temperature (t) of the time of the experiment, we get the specific gravity of the piece of sea-ice at the same temperature from the equation:

$$s = \frac{G}{G - g} \cdot p_t$$

¹⁾ Jermak Wa Ljedach, p. 395 foll., 414 foll.

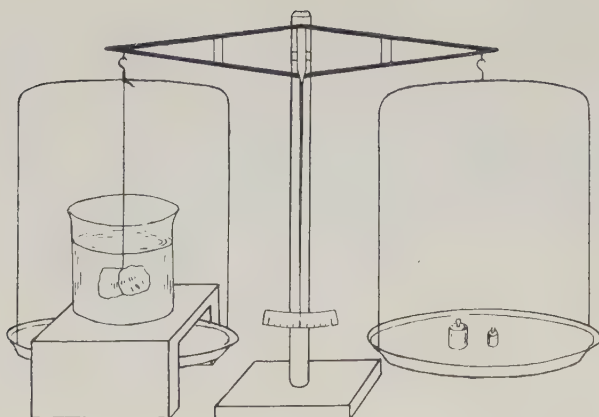


Fig. 3. Arrangement for determination of specific gravity of sea-ice.

In the weighing a correction of course must be made for the thin piece of iron wire on which the ice sample was suspended.

The specific gravity of the petroleum was determined at different temperatures by the weighing, in a measuring bottle, of a certain volume of petroleum (the uncorrected volume being 100.0 cc.). It proved that the p_t could be represented by the formula: $p_t = 0.833 - 0.00092 t$, where t was the temperature at the time of the experiment.

The advantage of using petroleum as a weighing liquid consists in the fact that this liquid does not force its way into the small holes filled with air which are found in certain kinds of ice. This was proved by the fact that g immediately became constant, no slow increase of g being detected. On one or two occasions the specific gravity of the ice was less than that of the petroleum, so that the piece of ice floated. In these cases the ice sample was loaded with a weight a , which was a little larger than was necessary to make the ice sink and a negative value of g was used in the formula.

Determinations of the specific gravity. Discussion of the results.

The results of the measurements carried out are summarized in Table 7.

Table 7.

No.	Date of Determ.	<i>G</i> gram	<i>g</i> gram	Spec. gravity at <i>t</i> ° referred to water at 4°.		<i>S</i> ‰	Depth of the sample cm.	Thickness of the ice cm.	Temp. at which the ice was frozen.
	1924				<i>t</i> °				
1 ¹⁾	5/2	175.7	10.5	0.915	— 29.0	14.6	3	5.5	Very low
2 ¹⁾	5/3	237.4	14.6	0.914	— 27.5	12.2	4	7	— 38
3 ¹⁾	1/2	256.45	17.4	0.920	— 26.5	8.7	13	26	— 30
4 ²⁾	Febr.	341.2	23.0	0.923	— 30.0	10.2	8	15	— 40
5 ²⁾	29/1	206.25	14.7	0.924	— 27.0	5.6	35	130	—
6 ³⁾	26/3	137.6	10.1	0.921	— 22.0	—	2	3.5	— 27
7 ³⁾	30/3	117.8	8.4	0.920	— 22.6	3.6	132	147	—
8 ⁴⁾	Febr.	244.1	16.7	0.923	— 29.0	0.0	2	Thick	—
8 a ⁴⁾	Febr.	332.3	24.7	0.919	— 19.0	0.0	2	Thick	—
9 ⁵⁾	Febr.	358.2	22.75	0.918	— 29.0	1.9	2	Thick	—
10 ⁶⁾	24/3	117.8	7.4	0.911	— 22.4	4.7	5	Thick	—
11 ⁷⁾	1/3	293.7	— 0.5	0.857	— 27.0	0.0	8	Thick	—
12 ⁸⁾	30/5	139.5	7.2	0.885	— 6.2	—	2	Thick	—
13 ⁸⁾	30/5	129.6	7.8	0.893	— 6.2	—	60	Thick	—
13 a ⁸⁾	30/5	205.0	12.0	0.891	— 6.2	—	60	Thick	—
14 ⁸⁾	30/5	42.3	2.5	0.892	— 6.2	—	75	Thick	—

Remarks. 1¹⁾ Screwed-up new-ice. 2²⁾ New-ice. 3³⁾ Screwed-up new-ice. 4⁴⁾ New-ice frozen out of fresh-water pond on big old-ice floe. 5⁵⁾ New-ice frozen in autumn out of water with small salinity. 6⁶⁾ Thick screwed-up new-ice, exposed to the sun for some time. 7⁷⁾ Top of "summered" ice. 8⁸⁾ Old ice samples, taken at the place where the ice-thermometers were laid out.

Before we examine in detail the values obtained, we shall first discuss somewhat more fully a few circumstances connected with the specific gravity (s) of sea-ice.

Earlier measurements have shown that s may vary within wide limits. Makaroff, for instance, found values of s that varied between 0.85 and 0.96. The cause of the variation lies mainly in the fact that the ice may contain considerable quantities of air or water. The air makes the ice lighter; the water makes it heavier.

The air in the ice may be derived either from the air in the sea-water or directly from the atmosphere. The air in the water is transmitted to the ice partly in the form of small air bubbles when the water freezes. Such bubbles occur in all sorts of sea-ice, although sometimes they may be so small that they cannot be detected with the naked eye. The quicker the ice freezes, the larger and more numerous are the bubbles. One consequence of this is that newly frozen ice usually contains more air in the topmost layers than it does lower down.

The other kind of air in sea-ice is derived, as has been said, directly from the atmosphere, and consists of air which penetrates into the ice from above during the late spring and summer. The course of this process has been described in detail by A. Hamberg¹⁾. Hamberg has shown that the ice in its upper layers melts *from within*, owing to its content of salt, in as much as the melting begins round the small cavities that contain brine. In the process of transformation to water the volume of the original particles of ice is diminished, and there is a tendency for small vacua to be formed within the ice. But these are immediately filled with air, which owing to the pressure of the atmosphere is forced in from above. The fact that they are not filled with sea-water is due to the circumstance that the ice below is tight. In the upper layers, however, it is porous owing to the fact that the melting "from within" begins in the topmost layer and does not penetrate deeper until later. If the melting has proceeded for a certain time, the ice becomes so porous that the brine trickles out and flows away in the small but deep runnels which are found everywhere on the surface of the ice in summer. In consequence of this still more air finds its way into the ice.

Ice that has weathered away in the way described above is very light so long as the weathered parts lie high enough to allow the water to run off. But if such weathered ice comes under the surface of the water owing to some cause or other, the pores are filled with water and we get instead an ice with a very high specific gravity.—Ice that drifts into an area where the temperature of the water is above 0° also becomes heavy, in as much as the same process which, according to Hamberg, takes place in the upper layers when the ice is exposed to warm air, now sets in the lowest layers owing to the influence of the warm water. But the cavities that are formed are now filled with water instead of air.

After what has been said with regard to the specific gravity of sea-ice in general we can now proceed to examine the results of our own determinations, which are set forth in Table 7.

Immediately below the table notes are given as to the character of the samples of ice investigated. From these notes and from the other data given in the table we find that samples 1—7 were taken from new-ice of varying salinity and thickness. *It is surprising that there are such small variations in the specific gravity as shown in these varied specimens of new-ice.*

The smallest values, 0.914 and 0.915, are shown by two thin and salt samples of new-ice (nos 1 and 2) which had frozen at a low temperature. The cause is surely

¹⁾ Axel Hamberg: Studien über Meereis und Gletschereis, Bih. till K. Sv. Vet. — Akad. Handlingar. Band 21. Avd. II No. 2.

to be found in the fact that more air-bubbles had been formed during the extremely rapid freezing of these bits of ice than would have been the case at a more normal rate of freezing. If we take sample 6, for instance, this sample has not an equally low specific gravity in spite of the fact that it is still thinner; in this case the freezing took place more slowly in consequence of the higher temperature.

Fairly thick samples of new-ice have a specific gravity of 0.92 throughout until the sun has begun its destructive activities in spring and summer. It has not been possible to show any appreciable change in the specific gravity with the depth, in spite of the fact that the depths of the samples vary from 8 to 132 cm. Nor does the salinity of the ice seem to play any very large part. The two samples which had frozen from comparatively fresh water (no 8 and 9), and which are therefore fresh, exhibit the same specific gravity as the others.

The agreement in the specific gravity of all new-ice which is found during the autumn and winter gradually ceases in the spring, when the sun rises above the horizon. As early as March 24 the specific gravity of the highest levels of screwed-up new-ice had diminished to 0.911, as appears from sample 10.

Pari passu with the progress of the above described weathering process in the summer, the specific gravity of the new-ice is diminished more and more not only in the topmost layers but also lower down. According to Table 7, the two-year-old-ice in which the ice thermometers had been placed in 1923—1924 had, as far down as a depth of 75 cm., a specific gravity indicative of weathering. If the specific gravity falls below 0.90, indeed, the number of air-bubbles alone enables one to observe directly that the ice has "summered".

The ice which in these experiments showed the smallest specific gravity was the top of a great floe of old-ice (sample 11: specific gravity 0.857). During the preceding summer this ice had lost its salt so entirely that in the winter it could be used as drinking water after melting.

IV. The Specific Heat, "Heat of Fusion" and Heat-Expansion of Sea-Ice.

General Remarks.

It may seem remarkable that we bring under the same heading such different properties as the specific heat, "the heat of fusion" and the heat-expansion of sea-ice; but this depends on the fact that all these quantities show abnormalities which are due to the same peculiar characteristic of sea-ice.

Otto Pettersson was the first to demonstrate that in the matter of heat of fusion and heat-expansion (the specific heat of sea-ice has never previously been investigated) sea-ice displays very noteworthy features¹⁾.

Thus Pettersson investigated the heat of fusion (P) in undercooled sea-water and found that P became smaller and smaller the saltier the water was. O. Krümmel²⁾ has summarized Pettersson's values in the following little table, which shows the dependence of the heat of fusion on the salinity when the change in the state of aggregation proceeds between -6° and -9° .

Salinity (‰).....	0	10	20	30	35	40
Heat of fusion (calories)	77	67.5	60.5	54.5	52	49.5

¹⁾ On the properties of water and ice. Vegaexpeditionens Vetensk. iakttagelser. Band 2. Stockholm 1883.

²⁾ O. Krümmel: Handbuch der Ozeanographie etc., p. 507.

Moreover Pettersson investigated the heat-expansion of sea-ice and found that abnormal too. Sea-ice, in fact, expands with falling temperature to a temperature limit which is -20° for very salt ice, but which for less salt ice lies considerably higher.

O. Krümmel ascribes these peculiar expansion conditions to the brine enclosed in the sea-ice. If the temperature of the sea-ice is lowered, ice is formed from the brine, and this process is connected with an increase of volume which more than compensates for the normal diminution in volume of the already existent ice.

Measurements during the "Maud" expedition have shown that Krümmel's hypothesis is right. Furthermore we have found that the abnormalities, which occur in the specific heat and "heat of fusion" of sea-ice also can be explained as consequences of the formation or melting of pure ice that takes place within the sea-ice. Thus the abnormally great specific heat of sea-ice at temperatures immediately below zero are due to the fact that even a small change in temperature involves a considerable change in the amount of pure ice per unit of volume: ice is melted or is formed, and in these processes great quantities of heat are stored up or liberated.

With regard to the "heat of fusion" of sea-ice we should like to point out that, if we regard the sea-ice as consisting of pure ice plus brine, we can no longer speak of a real "heat of fusion", for that conception is connected with a transition from a solid to a liquid state or vice versa at a *constant temperature*. As a matter of fact, however, sea-ice begins to melt at the lowest temperatures that occur in nature, and the melting goes on *continuously* with rising temperature until, at a certain temperature, *all* the ice is melted. In the following we are, therefore, concerned with the specific heat and the heat expansion only.

If the suggested explanation of the abnormalities is correct, it is possible approximately to compute the magnitude of the specific heat of sea-ice and its co-efficient of heat expansion.

Suppose that we have 1 gram of a sea-ice whose salinity is 1 ‰, and that A_τ grams of this sea-ice consist of pure ice at the temperature of τ . Suppose further that $A_\tau = f(\tau)$.

If the specific heat of the sea-ice at the temperature τ is c_τ we must, in order to raise the temperature from τ to $\tau + d\tau$, supply an amount of heat equal to $d\tau \cdot c_\tau$. Moreover if the specific heat for pure ice is c , the specific heat of the brine existing at the temperature τ is k_τ , and the heat of fusion of pure ice at the same temperature is λ_τ , $c_\tau \cdot d\tau$ must be equal to $A_\tau \cdot c \cdot d\tau$ (the amount of heat required to raise the temperature in A_τ grams of ice from τ to $\tau + d\tau$) $+ d\tau (1 - A_\tau) k_\tau$ [the amount of heat required to raise the temperature of $(1 - A_\tau)$ grams of brine from τ to $\tau + d\tau$] $+ \lambda_\tau \cdot dA_\tau$ (the amount of heat required to melt dA_τ grams of ice) $+ two other terms$ that however can be neglected because they always are very small compared to the sum of the former ones. One of these latter terms depends on heat effects accompanying the dilution or the concentration of the brine and the other is caused by possible heat effects of chemical nature. We thus get:

$$d\tau \cdot c_\tau = d\tau \cdot A_\tau \cdot c + d\tau (1 - A_\tau) k_\tau + dA_\tau \cdot \lambda_\tau \text{ or} \\ c_\tau = c \cdot A_\tau + k_\tau (1 - A_\tau) + \lambda_\tau \cdot f'(\tau).$$

Now the quantity $k_\tau (1 - A_\tau)$ is always very small in comparison with the sum of the other two terms. It may therefore be omitted and A_τ may be regarded as equal to 1. We thus get

$$c_\tau = c + \lambda_\tau \cdot f'(\tau).$$

If we on the other hand had a sea-ice with a salinity S , there would be melted instead, in the transition from τ to $(\tau + d\tau)$, a quantity of ice which is $S \cdot dA_\tau$. In this case, therefore, the equation would be

$$c_\tau = c + S \cdot \lambda_\tau \cdot f'(\tau).$$

In the same way it is easy to show that the coefficient of expansion of sea-ice at the temperature of τ ($u_{\tau cc}$) is equal to the coefficient of expansion of pure ice (α_{cc}) + a term which depends on the quantity of ice that is formed or melted in consequence of the change in temperature of one *cubic centimeter* of sea-ice (approximately = 0.92 grams). If the freezing at τ° of 1 g pure water is accompanied by an increase in volume equal to $\gamma_{\tau cc}$ we get the following equation, which is analogous to the preceding one:

$$u_{\tau cc} = \alpha_{cc} - 0.92 S \cdot \gamma_\tau \cdot f'(\tau).$$

Both $u_{\tau cc}$ and α_{cc} here refer to one cubic centimeter of sea-ice at the temperature of τ . In the following pages, however, we shall refer the coefficients of expansion (u_τ and α) to 1 gram of sea-ice or pure ice. In this case we get the simpler formula

$$u_\tau = \alpha - S \cdot \gamma_\tau \cdot f'(\tau).$$

If, further, α is put as equal to + 0.000169 and γ_τ as equal to 0.091, we get

$$u_\tau = 0.000169 - 0.091 S \cdot f'(\tau).$$

The computed specific heat of sea-ice at the temperature of τ (c_τ).

Previously it has been shown that, c_τ can be expressed by the equation

$$c_\tau = c + S \cdot \lambda_\tau \cdot f'(\tau)$$

where c is the specific heat of pure ice, S is the salinity of sea-ice, $f(\tau)$ is the amount of pure ice at temperature τ in 1 gram of sea-ice with a salinity of 1 ‰, and finally λ_τ is the heat of fusion of pure ice at temperature τ . If we express τ in centigrade we can, according to Persson, put λ_τ as equal to $80 + 0.5 \tau$, an equation which has been experimentally verified by Otto Pettersson¹⁾.

In order to compute $f'(\tau)$ we make use, for temperatures higher than -5° , of the relations that have been established by Martin Knudsen and H. J. Hansen. In the case of lower temperatures we employ Ringer's experimental results, of which an account has been given above.

We will start with the computation of $f'(\tau)$ for temperatures above -5° . If, as before we use A_τ to denote the quantity of pure ice which exists at the temperature of τ in one gram of sea-ice with a salinity of 1 ‰ we find that the corresponding salinity of the brine (S_τ) will be determined by the equation (p. 7).

$$(1 - A_\tau) S_\tau = 1.$$

From this we obtain

$$\frac{dA_\tau}{d\tau} = f'(\tau) = \frac{1}{S_\tau^2} \cdot \frac{dS_\tau}{d\tau}$$

The connection between the freezing temperature (r) and the specific gravity $(1 + \frac{\sigma_0}{1000})$ of sea-water is, according to Hansen²⁾,

$$r = 0.0086 - 0.064633 \sigma_0 - 0.0001055 \sigma_0^2.$$

¹⁾ Öfversigt af Kongl. Vetenskaps-akademiens Förhandlingar, 1878. No. 2. Stockholm.

²⁾ Öfversigt af Finska Vetenskaps Societetens Förhandlingar. Bd. 46, No. 6. Helsingfors 1904.

If we call the salinity of sea-water S , we have also, according to Martin Knudsen,

$$\sigma_0 = -0.093 + 0.8149 S - 0.000482 S^2 + 0.0000068 S^3$$

From these two formulae we obtain, on inserting a potential formula,

$$r = -0.0026 - 0.05265 S - 0.0000389 S^2 - 0.00000036 S^3 - 0.0000000012 S^4$$

If we apply this formula to the brine of our sea-ice, we obtain the following expressions for the relation between τ and S_τ :

$$\tau = -0.0026 - 0.05265 S_\tau - 0.0000389 S_\tau^2 - 0.00000036 S_\tau^3 - 0.0000000012 S_\tau^4.$$

This formula holds good with great accuracy between 0° and -2° and can also be used in the case of considerably lower temperatures. If we for instance use Ringer's measurements¹⁾ for computing S_τ values at -5.0° and -8.2° and insert the values found in the formula given above, we will find τ equal to -4.8° and -8.1° respectively. Thus the formula is sufficiently accurate at least as far down as -8.2° .

Now if we derive the formula in question and insert the reciprocal value of

$\frac{d\tau}{dS_\tau}$ in the expression for $f'(\tau)$, we get

$$f'(\tau) = \frac{1}{S_\tau^2} \cdot \frac{1}{0.05265 + 0.0000778 S_\tau + 0.00000108 S_\tau^2 + 0.0000000048 S_\tau^3}$$

By ascribing different values to S_τ we can compute simultaneous values of τ and $f'(\tau)$. If we later insert these values in the formula for c_τ , we can determine c_τ for different values of τ and S between 0 and -5 .

For lower temperatures we shall use an other method. Table 3 (p. 8) shows us how many grams of pure ice (B_τ) are found at the temperature τ in 1000 grams of sea-ice with a salinity of 35.05 ‰ (according to Ringer). The quantity of pure ice which is found at the same temperature in 1 gram of ice with a salinity of 1 ‰

(A_τ) will thus be $1 - \frac{1000 - B_\tau}{1000 \times 35.05}$ grams, because the brine including possibly solid salt in one gram of sea-ice of 35.05 ‰ weighs $\frac{1000 - B_\tau}{1000}$ grams and the corresponding

weight of brine in ice of 1 ‰ salinity will thus be $\frac{1000 - B_\tau}{1000 \times 35.05}$ grams.

The following little summary shows the weight in grams of the pure ice which is to be found at different temperatures in 1 gram of sea-ice with a salinity of 1 ‰: —

τ	-5.0°	-8.2°	-15.0°	-23.0°
A_τ	0.987746	0.991969	0.994602	0.996054

If these values are plotted in a system of coordinates with A_τ as ordinate and τ as abscissa, we obtain a series of points that can be connected by a curve. The derivative of this curve with respect to τ is evidently the function $f'(\tau)$, which is being sought. In order to obtain this, however, it is simplest to form the *mean values* of $f'(\tau)$ between the temperatures at which A_τ has been determined. The mean value

of $f'(\tau)$ between -5.0° and -8.2° , for instance, is $\frac{0.991969 - 0.98775}{8.2 - 5.0} = 0.001318$.

These mean values are then entered in a system of coordinates as rectangles with the temperature interval's as bases and the values of $f'(\tau)$ as heights. A continuous curve

¹⁾ W. E. Ringer: Ueber die Veraenderungen in der Zusammensetzung des Meereswassersalzes beim Ausfrieren. Verhandelingen uit Het Rijksinstituut voor Het Onderzoek der Zee. Helder 1906.

is then drawn by making the average length of the ordinates in a temperature interval (*e. g.* -5.0° to -8.2°) equal to the height of the corresponding rectangle. Evidently this curve represents $f'(\tau)$.

If we determine the value of $f'(\tau)$ for every even degree according to these two different methods, the use of which depends on whether τ is higher or lower than -5° , we get the values which are compiled in Table 8.

Table 8.

$\tau =$	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	-12
$f'(\tau) = \left\{ \begin{array}{l} 0.01307 \\ 0.05274 \end{array} \right.$				0.00319	0.00151		0.00084	0.00047		0.00031		
		0.00575		0.00201		0.00114		0.00061		0.00037		
$\tau =$	-13	-14	-15	-16	-17	-18	-19	-20	-21	-22	-23	
$f'(\tau) = \left\{ \begin{array}{l} 0.00027 \\ 0.00025 \end{array} \right.$		0.00024		0.00021		0.00018		0.00015		0.00012		
		0.00025		0.00023		0.00020		0.00017		0.00014		

Multiplying the values of $f'(\tau)$ by the corresponding values of λ_{τ} , we get a quantity which we shall call β_{τ} . The value of β_{τ} at different temperatures is given in Table 9.

Table 9.

$\tau =$	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	-12
$\beta_{\tau} =$	4.193	1.033	0.451	0.249	0.156	0.116	0.087	0.064	0.046	0.035	0.028	0.023
$\tau =$	-13	-14	-15	-16	-17	-18	-19	-20	-21	-22	-23	
$\beta_{\tau} =$	0.020	0.018	0.017	0.017	0.015	0.014	0.013	0.012	0.010	0.010	0.008	

According to what was said above, we know that

$$c_{\tau} = c + S \cdot \beta_{\tau}$$

and, as $c = 0.50$, we can thus, with the help of Table 9, compute the values of the specific heat of sea-ice (c_{τ}) at every temperature down to -23° . We have not carried the calculations further than -23° , for we have no direct measurements of the spec. heat at low temperatures and therefore have no possibility of ascertaining whether the theory any longer holds good in the simple form given above. At temperatures below -23° , in fact, *NaCl* begins to crystallize out in great quantities, and it is conceivable that this is accompanied by a heat effect, to which we have paid no attention in the above discussion.

We shall now pass to the direct measurements of the specific heat of sea-ice which were carried out during the "Maud" expedition of 1922–25, and see to what extent the results of these agree with the above-mentioned way of reasoning.

Determinations of the specific heat of sea-ice.

In the first determinations of the specific heat of sea-ice carried out during the "Maud"-expedition an ordinary calorimeter containing petroleum was used.

A piece of ice was weighed and suspended for several hours in air of constant temperature, after which it was brought into the calorimeter. The specific heat was determined according to the mixing method in the way laid down *e. g.* in Kohlrausch's „Lehrbuch der praktischen Physik“ (Leipzig u. Berlin 1910). This procedure, however, was both troublesome and unsatisfactory. In the first place it was difficult to maintain a constant temperature for a sufficient length of time to enable the whole piece of ice to assume that temperature; and in the second place the heat exchange in the calori-

meter took a very long time, which involved risks of great errors. Both these factors were due to the small heat-conductivity of the ice. Attempts were then made to break the ice into small pieces and place them in a bag of metal cloth, but then it became impossible to move the bag with the ice from the room with a constant temperature

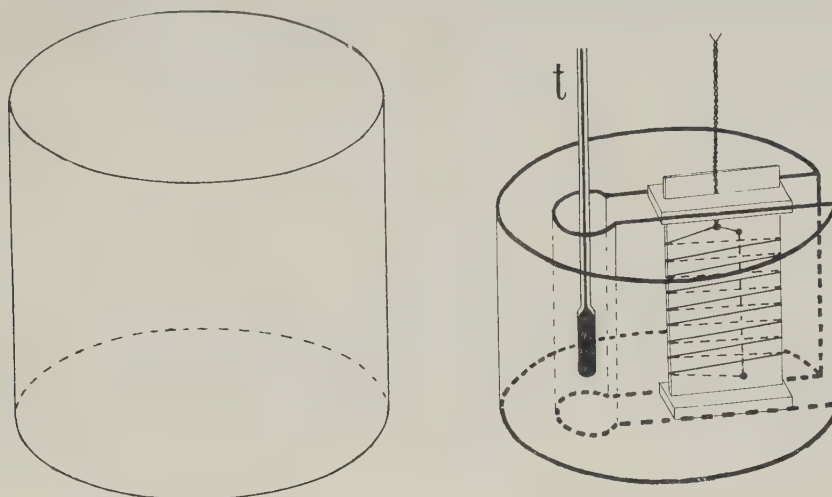


Fig. 4. Inner parts of electrical calorimeter for determining specific heat of sea-ice.

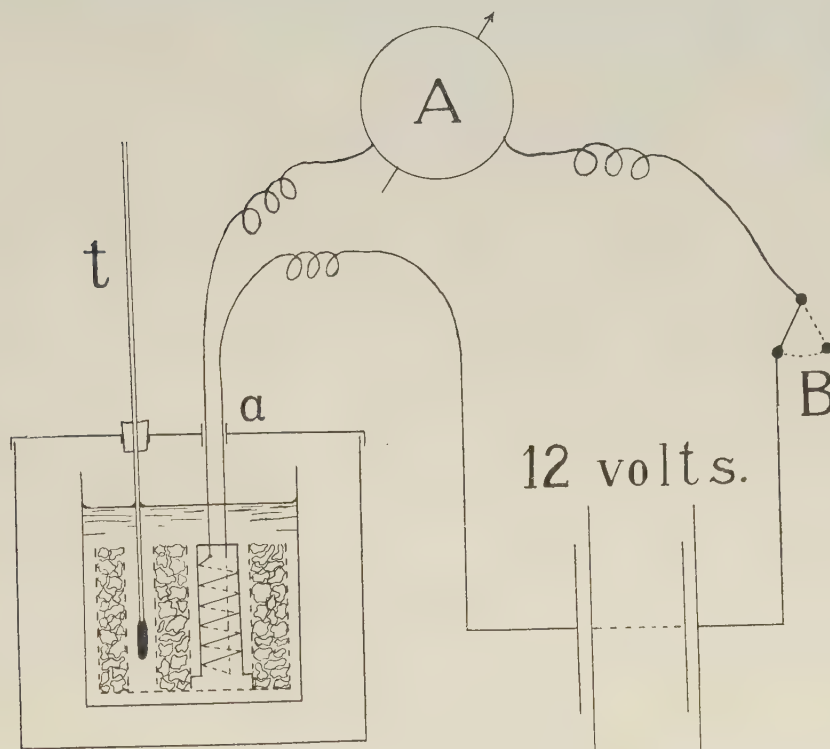


Fig. 5. Electrical calorimeter.

into the calorimeter without a change of heat. Finally an *electric* calorimeter was designed, which worked rather well.

The apparatus consisted of a small open vessel (left in Fig. 4), which stood on cork tips in a closed larger one (Fig. 5). The smaller vessel, which was filled with petroleum, formed the actual calorimeter. It contained a bag of brass cloth (right in

Fig. 4), which in the experiments was filled with small bits of ice. The bottom area of the bag was of almost the same size as that of the calorimeter, but its height was only two-thirds of the height of the latter. In the middle of the bag, but protected from the bits of ice by metallic cloth, was a heating wire of constantan, rolled round a thin, impregnated sheet of pasteboard. The heating wire ended in two isolated transmission wires of copper, which passed out through an opening (a) in the outer vessel (Fig. 5). The sheet with the heating wire was tied to the bag, in such way that the bag could be raised or lowered in the calorimeter vessel from the outside by means of the transmission wires, thus making an effective stirring in the calorimeter vessel possible. The temperature was read off on a thermometer (t), which was fastened to the outer vessel, and whose bulb stuck down into the protected space in the middle of the bag beside the hot plate. The thermometer did not move with the bag when that was raised or lowered.

The experiments were carried out on the deck of the "Maud" at an air temperature of -20° to -30° .—The ice which was to be investigated, was broken into small bits and stuffed into the calorimeter bag until this became quite full with the exception of the protected space in the middle of it. The bag with the ice was weighed. The calorimeter vessel and a suitable amount of petroleum was weighed. The bag was lowered into the calorimeter vessel, which was then placed in the outer vessel. The thermometer was placed in position and the heating wire was connected to a battery, and to a measuring instrument and a switch. The method of coupling is shown in Fig. 5. The ampèremeter (A) measured the strength of the current in the heating wires, and the switch (B) served to turn on or turn off the current, which was taken from a storage battery of twelve volts.

After the coupling had been effected, the temperature was observed every minute for a quarter of an hour, after which the current was allowed to pass for 2—6 minutes. While the current was on, the thermometer, and the ampèremeter were read repeatedly. After the current had been cut off, the temperature readings were continued for a further period of 10—20 minutes. After that the current was turned on for a new determination of c_t at a somewhat higher temperature. It was then turned off again for 10—20 minutes, turned on again, etc. In this way the investigation was carried on with alternating periods of current and non-current, until the temperature in the calorimeter had risen from the air temperature until -4° to -1° C. The observations of temperature between the periods when the current was on served to determine the loss of heat outwards during the supply of current. With their help it is possible to compute graphically the difference in temperature (T) which is caused solely by the current. The method is the same as that used in the calorimetric mixing experiments.

In order to calculate the specific heat of the ice, c_t , however, it is also necessary to know the weight of the bag and of the calorimeter vessel, and the water value (W) of the entire calorimeter. If we know these constants, we can compute c_t .

If the quantity of heat supplied is denoted by Q gram calories, we get

$$Q = 0.239 \cdot R \cdot i^2 \cdot t$$

where R is the resistance of the heating wire in ohms, i the strength of the current in ampères, and t is the number of seconds. If the difference in temperature caused solely by the current is T° , the weight of the ice I grams the weight of the petroleum F grams, and the specific heat of the petroleum b , we get the following equation, from which the specific heat of the ice (c_t) can be determined.

$$0.239 R \cdot i^2 \cdot t = T \cdot W + T \cdot c_t \cdot I + T \cdot b \cdot F$$

$$\text{from which } c_t = \frac{0.239 R \cdot i^2 \cdot t - T (W + b \cdot F)}{T \cdot I}$$

The water-value of the calorimeter was determined experimentally with pure water. The mean value obtained (7.2 gram calories) agreed fairly well with the value that had been computed from the weights of the different parts of the calorimeter and their respective specific heats (6.8 gram-calories). In the calculations the value 7.0 was adopted. The spec. heat of the petroleum was = 0.51. R was determined several times and proved to have a very small temperature co-efficient, as is shown by the appended table of the determinations:

Temperature	Resistance in ohms	Mean value
— 20°	{ 15.41 15.42	
± 0°	{ 15.40 15.45	15.42 Ω
+ 10°	{ 15.42 15.43	

The following instruments were used by the experiments:

1. *One precision ampèremeter* (Weston). One division equals 0.005 ampères; readings at 0.0005 ampères.

2. *One thermometer* (P. T. R. 57869), graduated in 0.2°. Corrections given in 2/100 degrees. Readings with an accuracy varying between 1/10 and 2/100, depending on the rapidity with which the temperature was changing.

Before I proceed to discuss the results of the measurements, I will cite as an example one of the determinations:—

Ice Specimen No. XI ($S = 7.96$ ‰).

Weighings

Calorimeter bag + ice	56.80 g	Calorimeter + bag + ice	94.2 g
Calorimeter bag empty	24.25 g	Previous weight + petroleum .	191.25 g
Ice	32.55 g	Petroleum	97.05 g

The temperature readings began at 10.21 a. m. and continued till 12.56. Extracts of the readings:

	Time	Degrees C	Strength of current
	10.30	— 19.1	
	.31	— 19.2	
	.32	— 19.3	
	.33	— 19.35	0.7390
	.34	— 19.45	0.7360
	.35	— 19.5	0.7350
	.38	— 19.7	0.7350
Current turned on at	.39.20 s	— 19.75	Mean 0.7362 amps.
39.m 20 sec. and	.40	— 19.7	
allowed to run for 3	.41	— 19.0	Resistance in heating
minutes.	.42	— 18.1	wire 15.42 Ω
	.43	— 16.6	Time 180 sec.
	.44	— 15.9	
	.45	— 15.5	
	.46	— 15.6	
	.47	— 15.8	
	.48	— 15.85	
	.49	— 16.02	

From this it is computed that $c_{\tau} = 0.54$ on the average for the range of temperature between -15.1° and -20.0° . ($T = 4.85^{\circ}$).

In the series that was carried out with the specimen of ice numbered XI, c_{τ} was determined at temperatures from -24° to -3° . For each determination there was obtained a mean value of c_{τ} for a certain interval of temperature, the magnitude of which varied between 5° and 2° . After these mean values of c_{τ} had been entered as rectangles with the temperature intervals as bases in a c_{τ}, τ system of coordinates, a continuous c_{τ} curve was drawn in such way that the mean value of c_{τ} within each interval was identical with the height of the corresponding rectangle. The value of c_{τ} was then read off at the mean temperature within each interval. The values found, together with values from similar series with other samples of ice, are compiled under the heading c_{τ} in Table 10. This table also contains τ and S and a *computed* c_{τ} ($c_{\tau comp.}$), which has been obtained from the β_{τ} values in Table 9. Finally, the table contains a column ($c_{\tau comp.} - c_{\tau}$), where the error in each determination is given under the supposition that the computed values are quite correct and a column with the same errors expressed in percentages of the theoretical c_{τ} values $\left(\frac{\Delta c_{\tau}}{c_{\tau comp.}} \cdot 100 \right)$.

Table 10.

Temperature τ	Salinity S	Observed spec. heat. c_{τ}	Computed spec. heat. $c_{\tau comp.}$	Δc_{τ} $= c_{\tau comp.} - c_{\tau}$	$\frac{\Delta c_{\tau}}{c_{\tau comp.}} \cdot 100$
— 1.6	4.72	6.51	8.19	+ 1.68	+ 20
— 2.3	4.72	3.91	4.14	+ 0.23	+ 6
— 2.8	7.56	5.19	4.47	— 0.72	— 16
— 4.1	7.56	2.56	2.28	— 0.28	— 12
— 4.2	7.96	2.50	2.26	— 0.24	— 11
— 4.6	4.72	1.53	1.36	— 0.17	— 12
— 5.0	7.56	1.94	1.69	— 0.25	— 15
— 5.7	7.96	1.33	1.51	+ 0.18	+ 12
— 6.2	4.72	1.14	1.02	— 0.12	— 12
— 6.5	7.56	1.60	1.26	— 0.34	— 27
— 6.7	8.80	1.32	1.34	+ 0.02	+ 1
— 7.7	4.72	0.84	0.83	— 0.01	— 1
— 8.4	7.56	0.96	0.92	— 0.04	— 4
— 8.5	8.80	0.93	0.97	+ 0.04	+ 4
— 9.2	7.96	0.82	0.84	+ 0.02	+ 2
— 9.5	4.72	0.72	0.69	— 0.03	— 4
— 9.9	7.96	0.75	0.78	+ 0.03	+ 4
— 11.0	7.96	0.70	0.72	+ 0.02	+ 3
— 11.6	4.72	0.61	0.62	+ 0.01	+ 2
— 12.0	7.96	0.65	0.68	+ 0.03	+ 4
— 12.1	7.56	0.61	0.67	+ 0.06	+ 9
— 13.1	4.72	0.56	0.59	+ 0.03	+ 5
— 13.2	7.96	0.62	0.66	+ 0.04	+ 6
— 13.7	8.80	0.78	0.67	— 0.11	— 16
— 16.0	4.72	0.60	0.58	— 0.02	— 3
— 17.0	8.80	0.53	0.63	+ 0.10	+ 16
— 17.5	7.96	0.54	0.61	+ 0.07	+ 11
— 20.0	8.80	0.52	0.61	+ 0.09	+ 15
— 21.0	4.72	0.56	0.55	— 0.01	— 2
— 22.5	7.96	0.57	0.57	0.00	0
— 3.6	0.00	0.51	0.50	— 0.01	— 2
— 5.9	0.00	0.49	0.50	+ 0.01	+ 2
— 8.4	0.00	0.50	0.50	0.00	0
— 11.0	0.00	0.56	0.50	— 0.06	— 12
					Mean 8.0

The last four determinations refer to pure ice ($S = 0.00$ ‰). Here we see that, apart from incidental variations, c_τ is *constant* and is very nearly equal to 0.50, which is the generally accepted value of the specific heat of pure ice between zero and -20° . The determinations are cited here only to give some idea of the accuracy of the calorimetric method employed.

In case of salt ice we see that c_τ increases very rapidly as τ approaches the freezing-point. This is in complete accordance with our earlier considerations, according to which the irregularities in c_τ are due to the formation or melting of pure ice in the sea-ice. The processes take place, mainly of course, at high temperatures where they may bring about a specific heat *which is several times greater even than that of the water*.

If we compare the c_τ values *quantitatively* with the values that we can theoretically compute from our previously ascertained β_τ values, we find that the *accordance between theoretical and observed values is good throughout*. The mean error in the observed values assuming the theoretical values to be quite correct, is only 8 ‰, in spite of the fact that the value of c_τ varies between 0.50 and 8.19 and that the salinity in the samples varies between 0.00 and 8.80 ‰. Only once among the 30 different determinations has there been found a c_τ value with an error of more than 20 ‰.

Whether the divergences from the theory are real ones, or whether they depend on incidental errors in the experimental values obtained by Ringer or myself, I feel myself unable to decide. Both Ringer's determinations of the amount of pure ice per gram of sea-ice and my own c_τ determinations, in fact, were subject to incidental errors which are sufficiently large to explain such divergences. In any case we cannot expect complete accordance between theory and observation because, as has been shown before, we have introduced a number of approximations in deducing the formulae.

The heat-expansion of sea-ice.

The best evidence that the above explanation of the abnormalities in the thermal properties of sea-ice is correct is to be found in the close agreement between the theoretical and observed values of the heat-expansion of sea-ice.

The heat-expansion of sea-ice was investigated on board the "Maud" in the spring of 1924. The apparatus that was used in the experiments consisted of a piece of iron tubing *A* (Fig. 6), one end of which was connected to a soldered iron-plate. The other end was open, but could be closed with a screw lid, which could be made completely air-tight by means of a leather packing.

Through the lid there passed a graduated glass tube *B*, fixed to it with a mixture of plaster and gum. Before the experiments the glass tube was calibrated by means of a small weighed column of mercury, whose length was determined at different places in the tube. In addition to this the volume of the iron vessel at a certain temperature was determined (124.3 cc. at $+12^\circ$). By means of the co-efficients of the heat expansion for iron and glass it was possible from these data to compute for each temperature the total of the internal volume of the iron vessel and the volume of the glass tube up to any given point.

For the experiments a cylinder with as nearly as possible the same shape and volume as the tube *A* was cut out of a block of ice. The ice cylinder was weighed and lowered into petroleum of low temperature, removing carefully all the remaining air-bubbles with a feather. After this the tube *A* was lowered into the petroleum and the walls of the iron tube were also freed from air-bubbles. While it was still lowered in the petroleum the piece of ice was introduced into the vessel *A*, after which the

lid was screwed on tight. The petroleum then rose in the glass tube and was forced out at its upper end. Only so much petroleum remained in the vessel A as was necessary to fill completely the empty space between the cylinder of ice and the vessel. After the lid had been screwed on, the whole apparatus was taken out of the petroleum, dried and shaken very violently in order to dislodge any airbubbles still clinging to the inner wall of the tube or to the surface of the sample. To be on the safe side the shaking was continued for several minutes after the last bubble had risen in the glass tube. The weight of the amount of petroleum (f) remaining in the apparatus after the sample had been inserted and the lid screwed on, was determined by weighing the apparatus both empty and when filled with ice and petroleum. As the ice had been previously weighed alone, the weight of the petroleum was obtained from the results of the last weighing deducting the weight of the apparatus and the ice.

The specific volume of the ice sample at a temperature of τ (W_τ) can now be computed if we read the height of the petroleum in the glass-tube. Suppose that it stands at a section which at temperature τ corresponds to a total inner volume of V_τ and further that the ice weighed g grams and that the specific weight of the petroleum at τ was φ_τ . We then get

$$V_\tau = \frac{f}{\varphi_\tau} + g \cdot W_\tau \quad \text{or} \quad W_\tau = \frac{1}{g} \left(V_\tau - \frac{f}{\varphi_\tau} \right)$$

The different temperatures were obtained by lowering the iron tube into a petroleum bath, where a certain temperature was maintained constantly for about four hours. Each sample was studied at rising as well as at falling temperatures. The specific volume at a certain temperature was taken as a mean of the values found in both cases.

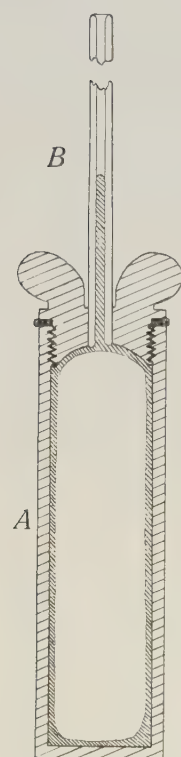


Fig. 6. Apparatus for determining heat-expansion of sea-ice.

The specific gravity of the petroleum was determined (0.833—0.00092 τ), and the co-efficient of expansion in volume for the iron, which enters into the computation of the V_τ , was assumed to be 0.000036. The volume of the iron pipe was assumed to be (124.200 + 0.000036 τ), but with an uncertainty of about 0.1 cc. The changes in volume during the experiments, on the other hand, were known with greater accuracy because 1 mm in the glass tube corresponded to a volume of about 0.00463 cc and the readings were taken with an accuracy of 0.1 mm. Hence the specific volumes given below may have an error of one unit in the third decimal place. These volumes have nevertheless been entered with five decimals, because the error in the two last decimals is equally great throughout, and consequently does not affect the computation of the co-efficient of heat-expansion, which, of course, is the derivative of the specific volume with reference to the temperature. In the experiments there were about 5 g of petroleum and 105—110 g of sea-ice in the apparatus.

The results of the three series of experiments which were carried out are given in Table 11. The co-efficient of heat-expansion (u_τ) has been computed from the values of the specific volume (W_τ) by entering the mean values of u ($= \frac{\Delta W_\tau}{\Delta \tau}$) as rectangles and then drawing a continuous u_τ curve in such a way that the mean value of u_τ within a certain interval is equal to the height of the corresponding rectangle.

Table 11.

Temperature t°	Salinity S‰	Volume at t of 1 gram sea-ice.	u_t Co-eff. of exp. unit: 1 gram sea-ice.	u_t Computed
— 3.5	10.22	1.07250	— 0.00475	— 0.00374
— 6.0	„	1.07976	— 0.00158	— 0.00123
— 10.0	„	1.08282	— 0.00039	— 0.00027
— 14.0	„	1.08370	— 0.00009	— 0.00006
— 18.0	„	1.08381	+ 0.00002	— 0.00002
— 22.0	„	1.08367	+ 0.00004	+ 0.00004
— 26.0	„	1.08347	+ 0.00006	—
— 32.0	„	1.08301	+ 0.00010	—
— 10.0	12.23	1.09261	— 0.00042	— 0.00035
— 14.0	„	1.09385	— 0.00021	— 0.00011
— 18.0	„	1.09440	— 0.00007	— 0.00005
— 22.0	„	1.09449	+ 0.00003	+ 0.00001
— 26.0	„	1.09424	+ 0.00010	—
— 30.0	„	1.09380	+ 0.00012	—
— 34.0	„	1.09325	+ 0.00015	—
— 38.0	„	1.09259	+ 0.00018	—
— 22.0	4.72	1.09914	+ 0.00008	+ 0.00011
— 24.0	„	1.09896	+ 0.00009	—
— 27.0	„	1.09872	+ 0.00010	—
— 30.0	„	1.09838	+ 0.00014	—
— 32.0	„	1.09807	+ 0.00017	—

In the column farthest to the right in Table 11 the values that have been computed from the formula $u_t = 0.000169 - 0.091S \cdot f'(t)$ have been introduced, for comparison. The agreement with the theory must be regarded as very good, especially if we take into account the primitive arrangement of the experiment, which must naturally involve errors in the experimental u_t values.

Far more exact determinations of the heat-expansion of salt ice have previously been carried out by Otto Pettersson¹⁾. These determinations, however, refer to air-free ice which has been produced artificially in the laboratory by freezing sea-water. Table 12 gives a summary of Pettersson's values together with the computed values of u_t for the same temperatures and salinities. Pettersson's values have been transferred to a unit of 1 gram sea-ice. *We see that Pettersson's determinations of u_t which were carried out with the greatest possible precision, accord very well with our theory.*

In spite of the fact that Pettersson's experimental arrangements were considerably better than those that it was possible to achieve on the "Maud", yet the "Maud" determinations possess their great value because they show that natural sea-ice, containing a great deal of air, has nearly the same co-efficient of expansion as the artificial salt ice which contains no air. *Thus the air-bubbles enclosed in sea-ice seem to play a subordinate part in the heat-dilatation of sea-ice.*

¹⁾ On the properties of water and ice etc.

Table 12.

Salinity 0.45 ‰			Salinity 6.69 ‰			Salinity 11.72 ‰		
τ	u_{τ} coeff. of exp. unit : 1 g. sea-ice	u_{τ} computed	τ	u_{τ} coeff. of exp. unit : 1 g. sea-ice	u_{τ} computed	τ	u_{τ} coeff. of exp. unit : 1 g. sea-ice	u_{τ} computed
— 1.6	— 0.00029	— 0.00067	— 3.2	— 0.00389	— 0.00287	— 6.4	— 0.00146	— 0.00128
— 2.6	— 0.00016	— 0.00015	— 4.2	— 0.00229	— 0.00155	— 7.2	— 0.00085	— 0.00097
— 4.6	+ 0.00009	+ 0.00007	— 5.2	— 0.00118	— 0.00098	— 8.2	— 0.00079	— 0.00067
— 5.6	+ 0.00011	+ 0.00010	— 6.2	— 0.00072	— 0.00069	— 9.2	— 0.00058	— 0.00045
— 6.6	+ 0.00013	+ 0.00012	— 7.2	— 0.00056	— 0.00049	— 10.2	— 0.00044	— 0.00030
— 7.2	+ 0.00013	+ 0.00012	— 8.2	— 0.00035	— 0.00031	— 11.2	— 0.00034	— 0.00021
— 9.2	+ 0.00015	+ 0.00015	— 9.2	— 0.00024	— 0.00018	— 12.2	— 0.00023	— 0.00015
— 11.2	+ 0.00016	+ 0.00016	— 10.2	— 0.00016	— 0.00010	— 13.2	— 0.00020	— 0.00011
— 13.2	+ 0.00016	+ 0.00016	— 11.2	— 0.00009	— 0.00004	— 14.2	— 0.00014	— 0.00009
— 14.2	+ 0.00015	+ 0.00016	— 12.2	— 0.00005	— 0.00001	— 15.2	— 0.00010	— 0.00009
— 15.2	+ 0.00016	+ 0.00016	— 13.2	— 0.00001	+ 0.00001	— 16.2	— 0.00008	— 0.00007
— 16.2	+ 0.00016	+ 0.00016	— 14.2	+ 0.00000	+ 0.00002	— 17.2	— 0.00004	— 0.00005
—	—	—	— 15.2	+ 0.00003	+ 0.00002	— 18.2	— 0.00003	— 0.00004
—	—	—	— 16.2	+ 0.00004	+ 0.00003	— 19.2	— 0.00001	— 0.00002

Tables summarizing the Values of specific Heat and Heat-expansion.

Supposing that the above formulae are correct we will close this chapter with some practical applications. At first we will use the formula $c_{\tau} = c + S \cdot \beta_{\tau}$ for computing the specific heat of sea-ice at different temperatures. The result of the computations is found in Table 13.

Table 13.

The spec. heat at different temperatures (τ) and salinities (S).

$\tau =$	— 2	— 4	— 6	— 8	— 10	— 12	— 14	— 16	— 18	— 20	— 22
$S = 2 \text{ ‰}$	2.57	1.00	0.73	0.63	0.57	0.55	0.54	0.53	0.53	0.52	0.52
$S = 4 \text{ ‰}$	4.63	1.50	0.96	0.76	0.64	0.59	0.57	0.57	0.56	0.55	0.54
$S = 6 \text{ ‰}$	6.70	1.99	1.20	0.88	0.71	0.64	0.61	0.60	0.58	0.57	0.56
$S = 8 \text{ ‰}$	8.76	2.49	1.43	1.01	0.78	0.68	0.64	0.64	0.61	0.60	0.58
$S = 10 \text{ ‰}$	10.83	2.99	1.66	1.14	0.85	0.73	0.68	0.67	0.64	0.62	0.60
$S = 15 \text{ ‰}$	16.01	4.24	2.24	1.46	1.02	0.85	0.77	0.76	0.71	0.68	0.65

In addition to Table 13 we will also compute how many gram calories (U) are required to just melt one gram of sea-ice of the temperature τ . The values may be of some importance as in the case of sea-ice we have no proper heat of fusion.

Let S be the salinity of the ice and τ_s the freezing point of a sea-water with the salinity S . If τ lies in the neighbourhood of zero the heat of fusion of pure ice between τ and τ_s can be considered constant and equal to 80 gram calories. The amount of heat required to just melt the sea-ice is then the sum of the heat required to melt all the pure ice in one gram sea-ice ($80 [1 - S (1 - A_{\tau})]$) and the amount of heat required to increase the temperature of the pure ice and brine from τ to τ_s .

[approximately $= 0.5 (\tau_s - \tau)$]. A_τ — as before the weight of all pure ice in 1 gram sea-ice with the salinity 1 ‰ and the temperature τ — is equal to $1 - \frac{1}{S_\tau}$ (p. 20), where S_τ is the salinity of the brine at τ . Thus

$$U = 80 \left(1 - \frac{S}{S_\tau} \right) + 0.5 (\tau_s - \tau);$$

From this formula the Table 14 is computed. We see from the table that very little heat is required for the melting of one gram of sea-ice when salinity and temperature are high.

Table 14.

Number of gram calories just required to melt 1 gram sea-ice of the temperature τ and the salinity S .

$S =$	0	2	4	6	8	10	15 ‰
$\tau = -1^\circ.0$	80	72	63	55	46	37	16
$\tau = -2^\circ.0$	81	77	72	68	63	59	48

Finally we shall use the formula $u_\tau = 0.000169 - 0.091 S \cdot f'(\tau)$ for computing the heat-expansion of sea-ice at different temperatures, compiling the results in Table 15.

Table 15.

The coefficient of volume expansion at different temperatures (τ) and salinities (S). Unit: 1 gram sea-ice. The coefficient is multiplied by 10^4 .

$\tau =$	- 2	- 4	- 6	- 8	- 10	- 12	- 14	- 16	- 18	- 20	- 22
$S = 2\text{‰}$	- 22.10	- 4.12	- 1.06	+ 0.16	+ 0.83	+ 1.13	+ 1.23	+ 1.27	+ 1.33	+ 1.38	+ 1.44
$S = 4\text{‰}$	- 45.89	- 9.92	- 3.81	- 1.37	- 0.02	+ 0.56	+ 0.78	+ 0.85	+ 0.96	+ 1.07	+ 1.18
$S = 6\text{‰}$	- 69.67	- 15.73	- 6.55	- 2.90	- 0.88	0.00	+ 0.33	+ 0.43	+ 0.60	+ 0.76	+ 0.93
$S = 8\text{‰}$	- 93.46	- 21.53	- 9.30	- 4.43	- 1.73	- 0.57	- 0.13	+ 0.02	+ 0.23	+ 0.45	+ 0.67
$S = 10\text{‰}$	- 117.25	- 27.34	- 12.05	- 5.95	- 2.59	- 1.13	- 0.59	- 0.40	- 0.13	+ 0.14	+ 0.42
$S = 15\text{‰}$	- 176.72	- 41.85	- 18.92	- 9.78	- 4.73	- 2.54	- 1.72	- 1.45	- 1.04	- 0.63	- 0.22

V. The Temperature of the Sea-ice.

General remarks.

The best observations of Arctic ice temperatures previously taken originate from the "Fram Expedition" 1893—1896. From March of 1894 until July of 1896 observations of the ice-temperatures were carried out by that expedition once or twice a day.

The mean temperatures at stated depths for the months of the year, computed by means of harmonic analysis from the mean values really found, are collected in Table 19 (p. 53)¹⁾. The formula used in analysis is

$$t_m = M + a \sin (A + m),$$

¹⁾ The Norwegian North-Polar Expedition 1893—1896. Scientific Results. Vol. VI, p. 562.

t_m being the mean temperature for the month, M the mean annual temperature, a the amplitude, A the phase-angle, and m the angle representing the month reckoned from the middle of January. We will, however, postpone the discussion of this table until we have set forth our own results.

According to the plan that Sverdrup had worked out for the scientific operations on board the "Maud", the ice-temperatures were to be measured at 3 to 5 different depths. The intention was to use the results of these measurements for the purpose of trying to find out the magnitude of the interchange of heat that takes place between air and sea. Sverdrup, who carried out the readings of the ice-temperatures, has placed the results and his notes at my disposition.

In 1922 the requisite instruments were obtained from U. S. A. They consisted of eight nickel resistance thermometers with a total length of 110 meters of three-strand, lead-isolated cable, and a temperature indicator with a spare galvanometer, all supplied by the firm of Leeds & Northrup Co. of Philadelphia. The resistance thermometers functioned quite satisfactorily the whole time, and can safely be recommended to future expeditions. The advantage of such thermometers in measuring temperatures in the ice is indeed very great, inasmuch as it is possible to dispense with keeping a hole open, which may disturb the normal distribution of temperature; also the errors are avoided which may arise when an ordinary thermometer is hauled up to be read.

It is not possible to obtain with nickel thermometers such accuracy as might have been desirable and as can be obtained with platinum thermometers. But the latter proved to be too costly, especially as the possibility had to be taken into account of losing several thermometers in the course of the expedition through the screwing-up of the ice. According to a statement from the factory, the sensitivity of the indicator in connection with the nickel thermometers was $\pm 0.3^\circ$, and the reading was guaranteed correct to $\pm 0.5^\circ$. According to our experience, however, both the sensitivity and the accuracy were considerably greater. Both by the continuity in the ice-temperatures read day by day at the greater depths and also by direct comparison with mercury thermometers it proved that the accuracy could be safely put at $\pm 0.2^\circ$. As regards sensitivity, it was soon noticed that the galvanometer made a distinct indication for a divergence of 0.1° from the temperature that gave non-current.

From October 10, 1922 to October 27, 1923 inclusive the ice-temperatures were measured exclusively with the resistance thermometers mentioned. Later, beginning on November 10, 1923, both resistance thermometers and thermocouples were used. How the measurements with the thermocouples were arranged and carried out will be described later on, when the observations during the winter of 1923—1924 are treated.

Measurements during the winter of 1922—1923.

A place for the resistance thermometers was selected at the beginning of October, 1922 on an ice-floe in the neighbourhood of the ship, 15 meters from an ice-house which was used for magnetic and atmospheric electric observations. The ice was fairly even on the surface, but the under-side might be uneven, for the spot belonged to an old-ice floe which had been exposed to screwing. The thickness was determined on October 2 as 2.50 meters; but even at a depth of 1.6 meters the water from below forced its way up into the bore hole. On October 6 three thermometers were placed in the ice at depths of 0.3, 0.8 and 1.6 meters. Three perpendicular holes were bored down at a distance of half a meter from one another, and the thermometers were stuck down in these holes in such a way that the middle of the 10 cm. long resistance coil came at one of the depths mentioned. The holes were after-

wards filled with water, which froze after a short time. The wires were led to a switchboard in the ice-house previously mentioned, where the measurements of the temperature were carried out every day about 8 a. m. At the same time the temperature at the "surface" was read with a toluol thermometer, which at first was stuck down in a little hole in the ice, but later, when the ice had become covered with snow, was placed about 2 cm. down in the close-packed snow.

The temperatures entered in the tables for the winter of 1922—1923 under the heading "Surface" thus refer to the actual surface of the ice if the ice was bare but to the surface of the snow above the spot where the thermometer was placed if the ice was covered with snow. During the autumn the ice at the thermometer place was usually bare. In winter, on the other hand, the snow conditions varied greatly, inasmuch as driven or fresh snow often settled over the place but was soon cleared away. In the spring it proved impossible to keep the place of observation free from snow, and consequently the snow was allowed to remain after March 5. See remarks on the snow conditions below.

Before the resistance thermometers were placed in position, they were compared with a mercury thermometer whose corrections were known. In August 1923 two of the resistance thermometers were again compared with a normal thermometer; the third had been lost.

The results of these comparisons are brought together below:

Date	Temp. at the comparison.	Correction of thermometer no.		
		75081	75084	75083
October 5, 1922.....	— 13.2	+ 0.1	0.0	+ 0.1
August 24, 1923.....	— 0.2	+ 0.2	—	+ 0.1
	— 15.5	+ 0.2	—	+ 0.1
Correction used		+ 0.1	0.0	+ 0.1
Depth of thermometer.....		0.3 m.	0.8 m.	1.6 m.

It will be seen that the corrections lie within the limit assumed for the accuracy of the resistance thermometers; but as the above values for the corrections have been obtained twice with the interval of a year, they have been considered real and applied to all temperature readings.

The snow conditions of the place where the ice-thermometers were deposited are illustrated by the following summary:

Date	Remarks.
1922	
9/10—22/11	Ice free from snow.
23/11	1 cm. new-fallen snow.
25/11	2 cm. new-fallen snow, removed at 10 a. m.
4/12	From 6 p. m. on 3/12 until 6.30 next morning 4 cm. new-fallen snow.
10/12	Drifting snow covered the thermometers 7/12—10/12. In clearing the place at 10 a. m. on 10/12 8 cm. snow was removed.
13/12	About 8 cm. of drifting snow from 12/12, removed at 7 a. m.
16/12	About 5 cm. of drifting snow; removed at noon.
27/12	About 5 cm. of drifting snow; removed at 11 a. m.
1923	
1/1	About 4 cm. of drifting snow; removed at 11 a. m.
6/1	3—5 cm. of drifting snow; removed at 9.30 a. m.
16/1	About 8 cm. of drifting snow; removed at 9.30 a. m.

Date	
30/1	About 5 cm. of drifting snow; removed at 9 a. m.
5/2	3—8 cm. of drifting snow; removed at 9 a. m.
12/2	11—15 cm. of drifting snow; removed at 9 a. m.
15/2	About 6 cm. of new-fallen snow; removed at 6.30 a. m.
19/12	10—20 cm. of drifting snow; removed at 6.30 a. m.
21/2	25—30 cm. of drifting snow; removed at 9 a. m.
26/2	23/2—26/2, various heights of drifting snow; about 25 cm. removed 26/2 at 9.30 a. m.
5/3	1/3—5/3 various heights of drifting snow; removed 5/3 at 10 a. m.
8/3	About 30 cm. drifting snow.
8/3—10/6	30—40 cm. of hard-packed snow over the place where the thermometers were deposited.

The snow conditions exert a very great influence on the ice-temperatures. If the ice is covered with snow, in fact, the temperature at the same depth, counted from the upper edge of the ice, is considerably higher than it would be otherwise, owing to the small capacity of the snow to conduct heat. The observations that were begun in 1922 were intended at first to investigate the temperature of ice without a covering of snow, but as the place could not be kept free from snow as spring advanced, the original plan had to be abandoned. The effect of this is that the series of temperatures during the period October 1922—August 1923 lack homogeneity in some degree. The series does not apply either to the ice which during the cold periods of the year is constantly bare or to the ice with a normal undisturbed snow-covering, but to an ice which is bare in autumn and to a large extent also during winter, but which becomes covered with snow later in the spring.

In order to demonstrate the effect of the snow-covering another resistance thermometer was deposited in the ice on January 12, 1923 (no. 75081, with a correction $= + 0.2^\circ$). It was placed at a depth of 0.1 m. under the upper surface of the ice, about 5 meters nearer to the ice-house than the others. The snow above this thermometer was allowed to remain undisturbed. The thickness of the snow covering this thermometer was about 25 cm. in the middle of January, about 35 cm. in February, and about 40 cm. from the beginning of March till the snow began to melt.

The snow began to melt in the middle of June 1923 and it went on so long that the melting of the ice itself did not set in till the last days of that month. The cables down to the ice-thermometers were marked at the original surface of the ice, so that it was possible to determine the magnitude of the melting by measuring the distance from these marks down to the new ice surface. The result of these measurements is shown in the Table 16.

Table 16.

Date 1923	Thickness of ice stratum thawed away	Date 1923	Thickness of ice stratum thawed away
30 June	15	6 Aug.	120
9 July	35	11 „	129
18 „	55	16 „	136
25 „	75	20 „	141
31 „	90		

It will be seen that the melting was very great. But the measurements cannot claim any great general importance, mainly because the ice melted at different rates in different places. The neighbourhood of the vessel certainly *increased* the melting of the floe in question inasmuch as a number of small particles coming from the ship (dust etc.) settled on the surface of the floe there hastening the melting. Hence no claim is made that the figures measured represent the *average melting*, but in any case they give an approximate idea of the magnitude of the melting and of the rate at which that process went on during the different weeks of the summer.

The thickness of the ice was not measured during the winter owing to defects in our ice augers, which were not suited for use in severe cold. In June, July and August however, it was determined a few times.

The results of all the measurements are given below:

2 Oct. 1922,	thickness of ice	250	cm.
20 June	" " "	334	"
18 July	" " "	287	"
7 Aug.	" " "	285	"
20 Aug.	" " "	265	"

All the bores were made within an area of about 1 square meter, but in spite of this it is by no means certain that they give a quite correct picture of the changes in the thickness of the ice. When it is a question of an old-ice floe, in fact, there is always a risk that the underside is uneven, and consequently that the ice has a somewhat different thickness even in places quite close to one another.

In the course of the summer the thermometers were deposited at greater depths as they came nearer the surface by melting. On August 20, 1923 the thermometers were dug up in order to be compared with a normal thermometer. In the course of this work, which was very troublesome owing to the fact that the hole which had to be cut in the ice was gradually filled with water, the deepest thermometer was lost in consequence of the cable being cut through.

Measurements during the winter of 1923—1924.

On August 24, 1923 a fresh spot was chosen for placing the ice-thermometers, this time in ice that had frozen the preceding autumn. This ice was chosen because it might be expected that the underside would be more or less even, inasmuch as we knew that it had never been exposed to screwing. Four resistance thermometers were placed in position; one on August 24 at a depth of 120 cm.; two others on September 2 at a depth of 25 cm. and 70 cm. respectively; and finally one on October 18 at a depth of 200 cm.

In comparisons with the normal thermometer carried out on August 24 the following corrections were determined over a temperature interval of 0 to -15° :

Thermometer no.	75078	75082	75081	75083
Depth in cm.	25	70	120	200
Corrections from 0° to -15° ...	+ 0.1°	+ 0.3°	+ 0.2°	+ 0.1°

These corrections have been applied to the readings. The correction for 75083 proved to be doubtful, however, possibly owing to the fact that the cable was slightly damaged when being placed in position. It was probably + 0.4° . As the nine days' readings with this thermometer had to be regarded as uncertain, however, they have not been included in the table.

The ice was practically free of snow in September and October, but the temperatures may possibly have been affected in some degree by a channel 60 cm. deep situated three meters from the thermometers. The water in this channel froze only gradually during the course of September and the first half of October.

The thickness of the ice was measured several times. The borings were all made on a stretch of ice two meters long between the thermometers and the channel mentioned above. The results were as follows:

Date	Thickness	Remarks
24/8/23	260 cm.	Loose ice from 180 cm. down.
4/9/23	245	Two borings.
19/9/23	225	Two borings.
6/10/23	211	
18/10/23	200	

On the night between October 27 and 28 all the thermometers were lost, as the ice floe to which the "Maud" had frozen was ground to pieces in the course of a violent screwing.

In the beginning of November the ice conditions again became so quiet that we could contemplate setting out fresh thermometers, but it was considered too risky to deposit our last resistance thermometers after the repeated screwing that had occurred of late. We had however an abundant supply of copper wire and some constantan wire, which could be put together to form thermocouples, the current in which could be measured with a very sensitive portable galvanometer (1 division = 3.88×10^{-6} ampères) which was available on board. Consequently we resolved to use thermocouples in the future measurements of ice-temperatures.

The arrangement that Sverdrup devised to measure the ice-temperatures was very simple. Along a wooden bar, well three meters long, was fastened an insulated constantan wire, to which six insulated copper wires were soldered. The distance from the topmost soldering-place to the others was 25, 75, 125, 200 and 300 cm. respectively. The bar with the wires was thrust down through a hole in the ice until the topmost soldering-place was on a level with the upper surface of the ice. The ends of the copper wires were led to a switchboard on the ice. Two of these wires, together with intervening piece of constantan wire, now formed a thermocouple, which gave a current proportional to the difference in temperature between the junctions. The thermocouples were placed in position on November 9. The hole that had been bored for the purpose soon froze over, and at the same time all the junctions froze into the ice except the lowest one, which projected down into the water. The thickness of the ice at the time, in fact, was only 2.40 m. By coupling the galvanometer to the switchboard it was now possible to measure the thermo-electric currents which arose in the couple 0—25 cm., 25—75 cm. and so on. All the thermocouples had an equally great resistance, so that they gave the same current for the same difference in temperature. (For copper-constantan couples the thermo-electric power varies so little with the mean temperature of the junctions that the variation can be ignored in the present case; and the same holds good for the variations in the resistance with the temperature). Owing to the fact that all the thermocouples had the same resistance, the various differences in temperature could be conveniently computed from the respective strengths of the current in accordance with one single determination of the scale value of the galvanometer. The equality in the resistance also had the effect that the scale value could be determined by simply dividing the difference in temperature between the topmost and bottommost junctions by the sum of

all the five galvanometer readings. The difference of temperature in question could be obtained by placing a thermometer close to the top junction, reading the temperature and diminishing the value by 1.5° . The bottom soldering-place, in fact, had the temperature of the water, which throughout the winter remained constant at -1.5° . Such a determination of the scale value was carried out each time and formed the basis of the computation of the differences in temperature. The actual temperatures were afterwards obtained by starting from the temperature of the uppermost soldering-place and adding the several differences one by one. The reading of the galvanometer took place every day, as a rule, between 12^h and 13^h. In the act of reading the observer had no protection but knelt on his knees exposed to wind and weather, and read off the galvanometer, which at the time of the observation was placed immediately on the ice about three meters from the thermometer.

In the winter of 1923—1924 the readings of the thermometer at the topmost thermocouple were entered under the heading "0.00 m.". *That year, therefore, the temperature of the actual surface of the ice was measured throughout*, in contrast to the preceding year, when the "surface-temperature" at times referred to the temperature of the overlying snow surface. In the year 1923—1924 also, however, the ice was at times covered with snow.

The thermocouples were set out, as has been mentioned before, on November 9, 1923. The measurements were carried out and computed in the way described above down to the close of March, 1924 and appear to give reliable values. In order to control them two resistance thermometers were let down in the beginning of March at depths of 25 and 200 cm. These gave temperatures that almost exactly coincided with those of the thermocouples at the same depth, as is shown by the following summary, covering the period March 5—31:

Depth cm.	Thermocouple	Temperature	
		Resistance thermometer	
25	— 25.47	—	25.70
200	— 9.70	—	9.71

The readings of the resistance thermometers are here corrected after comparison with a normal thermometer. For both thermometers the correction was fixed at $+0.3^{\circ}$ at 0° and $+0.5^{\circ}$ at -32° .

The close agreement between the temperatures of the thermocouples and of the resistance thermometers justifies the belief that both methods of measuring yield correct results. Nevertheless the thermocouples seem to be affected by greater occasional errors, as is shown by the irregular changes from day to day at the greater depths.

From the beginning of April the temperatures measured at the depths of 25 and 200 cm. were made the basis of the calculation of the scale-value of the galvanometer. This was rendered necessary by the fact that the temperature at 300 cm. began to decline at the close of April because the thickness of the ice had increased so much that the junction at that depth also had become frozen in. As to the thickness of the ice, therefore, we know that it was 240 cm. on November 9 and 300 cm. about April 15. No further measurements of this matter were made.

The snow conditions during the winter of 1923—1924 above the ice-thermometers were "natural" — that is to say, no attempt was made to clear away the snow or otherwise interfere with the thickness of the snow covering. But as the ice—though an old-ice floe—had a level upper side, but little snow settled over the place, only 3 to 5 cm. of firm snow on an average.

The snow conditions are shown in the following summary:

		Remarks.
Date 1923		
Sept.	Oct.	Ice, free from snow.
30/11/23		3—4 cm. of snow.
1924		
1/1/24		About 4 cm. of hard-packed snow.
31/1/24		About 4 cm. of hard-packed snow.
28/2/24		About 4 cm. of hard-packed snow.
30/3/24		A few cm. of snow, over this a little hoarfrost.
6/4/24		A few cm. of hard-packed snow.
18/4/24		1—2 cm. of new-fallen snow over the old hard-packed snow.
25/4/24		A few cm. of snow, hardened by the influence of the sun.
12/5/24		4—5 cm. of soft snow.

At the close of April, 1924, when the temperature of the air showed a large daily variation, the temperature at the depth of 25 cm. of ice was measured every other hour during the course of a couple of days in order to investigate whether any daily oscillation in temperature could be proved to exist at that depth.

It was found that the temperatures at 0.25 m. read off at noon were only slightly affected by the daily period, the deviation from the real daily mean being not more than 0.1° . At 0.00 m. the temperatures were 2° too high. In accordance with this the monthly mean of the temperature at 0.00 m. during March—the last month when the 0.00 temperatures were read off—must be lowered from $-27^{\circ}.8_5$ to $-29^{\circ}.1$.

Simultaneously with the depositing of the thermocouples in the ice for the measurement of its temperatures, in November, 1923 two special thermopiles were laid out for measuring the *temperature gradients* at the depth of 25 cm. and 200 cm. respectively. They consisted of a large number of series-coupled copper-constantan thermocouples, whose junctions were collected into two bunches, at a distance of about 10 cm. from one another. With the help of these thermocouples the difference in temperature between 20 and 30 cm. and between 195 and 205 cm. could be established with an accuracy of about $1/20^{\circ}$. The way in which these gradients, can be used for the computation of the heat conductivity of the ice will be shown later.

At the beginning of May, 1924 the floe to which the "Maud" was frozen fast was broken up, and the piece with the ice thermometers was carried 300—400 meters away. The distance between the ship and the thermometers gradually increased afterwards in the course of May and the beginning of June owing to repeated screwings of the ice, one effect of which was that the readings could no longer be made regularly. After June 9 the measurements had to be abandoned. On a later occasion one of the resistance thermometers was successfully recovered, but the other thermometer and all the thermocouples were lost.

Tables.

The following tables give the *observed* temperatures, corrected for the errors of the thermometers and the thermocouples. The only exceptions are formed by the tables for July and August, 1923, where the observed temperatures are reduced to constant depths. During those two months, in fact, the depths of the thermometers changed very rapidly from day to day, while the temperature at a certain depth was very constant. In order to get rid of the variations in the depths and to increase the

comprehensibility of the results, therefore, the temperatures have been reduced to certain definite depths by means of graphic interpolation. This has been done in the following way: The temperatures read on the same thermometer for five (or, in exceptional cases, six) days have been summarised to averages referring to the mean depth of the thermometer in question during those days. The mean temperatures of the five-day periods have then been set out in curves representing the variation of the temperature with the depth during the period. From these curves the temperatures for 0.00, 0.25, 0.75, 1.25 and 2.00 meters respectively have been read off.

Occasionally it has happened that it was impossible to determine the temperatures, in which cases the values have been interpolated and are set out in brackets. These interpolated values have afterwards been included in the computation of the monthly averages. The observations on the ice-floe which broke up on October 28, 1923 have also been incorporated with the measurements of temperature which were started on a new floe on November 10 in the same year by the "interpolation" of the intervening days. The interpolated values here have nothing directly corresponding to them in nature, as the interpolation is made between series of temperatures referring to two different ice-floes. But the ice-temperatures of the two floes were in all probability so similar that the monthly averages for October and November, which are formed with the help of these imaginary values, are better than averages derived solely from the values on the first or last days of the month. In all interpolations attention has been paid to the temperature of the atmosphere during the missing space of time. This was done by making out and studying on each occasion curves showing the temperature of the atmosphere and the temperature of the ice at different depths.

1922 October.

Day	8 a. m.			
	Surf.	0.3 m.	0.8 m.	1.6 m.
1	—	—	—	—
2	—	—	—	—
3	—	—	—	—
4	—	—	—	—
5	—	—	—	—
6	—	—	—	—
7	—	—	—	—
8	—	—	—	—
9	—	—	—	—
10	—11.0	—7.5	—3.2	—1.2
11	—	—	—	—
12	—10.2	—7.5	—3.3	—1.2
13	—14.6	—7.7	—3.3	—1.3
14	—9.0	—7.4	—3.5	—1.4
15	—7.7	—7.1	—3.6	—1.5
16	—13.0	—7.5	—3.5	—1.5
17	—11.9	—7.8	—3.6	—1.5
18	—13.4	—8.5	—3.7	—1.5
19	—13.0	—8.8	—4.0	—1.5
20	—9.3	—7.8	—4.2	—1.5
21	—5.8	—6.6	—4.3	—1.4
22	—9.0	—6.2	—4.1	—1.5
23	—16.5	—7.0	—3.9	—1.5
24	—13.7	—8.5	—3.8	—1.5
25	—19.6	—9.5	—4.4	—1.5
26	—23.5	—11.7	—4.9	—1.5
27	—18.3	—13.3	—5.7	—1.6
28	—15.5	—13.0	—6.7	—1.6
29	—19.0	—12.8	—6.9	—1.8
30	—15.4	—11.9	—7.1	—1.9
31	—17.8	—12.7	—7.4	—1.9
Mean 10—30	—13.68	—9.09	—4.53	—1.51

1922 November.

Day	8 a. m.			
	Surf.	0.3 m.	0.8 m.	1.6 m.
1	—8.7	—10.7	—7.5	—1.9
2	—8.8	—8.9	—7.2	—2.1
3	—15.0	—8.9	—6.7	—2.1
4	—24.8	—12.9	—6.8	—2.2
5	—23.0	—14.7	—7.6	—2.3
6	—25.3	—16.0	—8.5	—2.5
7	—23.7	—16.4	—9.4	—2.6
8	—19.7	—15.4	—10.0	—2.9
9	—19.7	—14.9	—10.0	—3.0
10	—27.0	—16.9	—10.1	—3.2
11	—32.3	—19.8	—10.9	—3.5
12	—25.0	—20.1	—12.0	—3.7
13	—23.0	—18.4	—12.6	—3.9
14	—22.6	—19.0	—12.7	—4.2
15	—22.7	—19.4	—12.8	—4.4
16	—21.3	—18.9	—13.0	—4.7
17	—25.2	—19.6	—13.0	—4.9
18	—25.6	—19.4	—13.4	—4.9
19	—25.7	—19.9	—13.5	—5.0
20	—29.0	—21.4	—13.8	—5.2
21	—26.1	—21.7	—14.3	—5.4
22	—23.3	—20.0	—14.6	—5.6
23	—27.6	—20.2	—14.5	—5.9
24	—29.0	—20.4	—14.6	—6.0
25	—31.0	—23.2	—15.0	—6.1
26	—21.0	—20.7	—15.5	—6.3
27	—23.0	—18.2	—15.1	—6.4
28	—34.0	—22.1	—14.6	—6.4
29	—19.8	—22.4	—15.3	—6.5
30	—27.9	—21.3	—15.3	—6.5
Mean	—23.69	—18.06	—12.01	—4.34

1923 January.

Day	8 a. m.			
	Surf.	0.3 m.	0.8 m.	1.6 m.
1	-30.0	-21.0	-15.1	-7.5
2	-32.7	-22.2	-15.2	-7.5
3	-32.6	-23.2	-16.3	-7.6
4	-33.0	-23.9	-16.6	-7.8
5	-27.2	-23.4	-17.1	-8.0
6	-32.1	-22.1	-17.1	-8.3
7	-30.5	-23.4	-17.1	-8.4
8	-29.0	-23.0	-17.5	-8.5
9	-30.0	-22.9	-17.2	-8.6
10	-29.3	-22.9	-17.2	-8.8
11	-33.2	-22.7	-17.4	-8.9
12	-38.2	-24.9	-17.6	-8.9
13	-38.6	-26.4	-18.4	-9.0
14	-39.5	-27.4	-19.1	-9.1
15	-38.0	-27.9	-19.6	-9.3
16	-33.0	-27.0	-19.9	-9.5
17	-31.0	-24.5	-20.0	-9.6
18	-37.3	-26.0	-19.2	-9.8
19	-31.4	-25.3	-19.2	-9.9
20	-37.0	-25.5	-19.0	-9.9
21	-34.0	-25.9	-19.0	-9.9
22	-36.4	-24.7	-19.0	-9.9
23	-39.4	-24.1	-18.9	-9.9
24	-40.3	-25.7	-18.8	-9.9
25	-42.2	-28.4	-19.6	-10.0
26	-38.3	-28.4	-20.5	-10.2
27	-33.2	-26.3	-20.5	-10.4
28	-31.0	-24.4	-19.6	-10.7
29	-31.0	-23.8	-18.5	-10.7
30	-38.4	-23.0	-18.5	-10.7
31	-39.4	-25.7	-18.1	-10.6
Mean	-34.43	-24.71	-18.28	-9.28

1922 December.

Day	8 a. m.			
	Surf.	0.3 m.	0.8 m.	1.6 m.
1	-23.6	-21.6	-15.4	-6.7
2	-22.8	-19.8	-15.2	-6.8
3	-29.2	-19.9	-15.0	-6.9
4	-24.3	-19.4	-15.1	-6.9
5	-18.3	-17.8	-15.0	-6.9
6	-27.1	-19.5	-14.5	-6.9
7	-19.9	-19.8	-14.8	-6.9
8	-15.9	-17.2	-14.5	-6.9
9	-24.0	-18.4	-14.0	-6.9
10	-19.0	-18.0	-14.0	-6.9
11	-19.1	-16.8	-13.8	-6.9
12	-23.7	-17.3	-13.5	-6.9
13	-21.9	-17.9	-13.3	-6.9
14	-22.1	-17.1	-13.4	-6.9
15	-23.9	-18.3	-13.3	-6.8
16	-21.7	-17.9	-13.5	-6.7
17	-26.1	-18.9	-13.5	-6.7
18	-26.0	-19.4	-13.7	-6.7
19	-28.0	-20.2	-14.0	-6.8
20	-25.9	-20.3	-14.4	-6.8
21	-23.2	-20.0	-14.7	-6.9
22	-20.3	-18.4	-14.5	-6.9
23	-23.7	-18.4	-14.1	-7.0
24	-30.8	-20.1	-14.2	-7.1
25	-31.7	-21.6	-14.9	-7.2
26	-26.9	-21.1	-15.4	-7.3
27	-23.6	-19.8	-15.4	-7.3
28	-31.2	-20.9	-15.0	-7.4
29	-24.8	-20.0	-15.2	-7.5
30	-30.3	-20.8	-15.0	-7.5
31	-26.4	-20.7	-15.1	-7.5
Mean	-24.37	-19.27	-14.43	-6.98

1923 February.

Day	8 a. m.				
	Surf.	0.3 m.	0.8 m.	1.6 m.	0.1 m.
1	— 38.0	— 26.9	— 19.4	— 10.5	— 19.3
2	— 35.0	— 24.8	— 19.8	— 10.5	— 19.3
3	— 35.3	— 26.0	— 20.0	— 10.6	— 19.2
4	— 34.9	— 27.4	— 19.7	— 10.7	— 19.5
5	— 32.2	— 25.5	— 19.9	— 10.7	— 19.4
6	— 38.0	— 24.9	— 19.1	— 10.6	— 19.2
7	— 30.0	— 25.4	— 19.2	— 10.7	— 19.7
8	— 27.7	— 23.4	— 19.1	— 10.7	— 19.1
9	— 30.2	— 23.4	— 18.7	— 10.7	— 18.5
10	— 27.1	— 24.5	— 18.8	— 10.7	— 19.0
11	— 8.0	— 20.9	— 18.5	— 10.7	— 17.5
12	— 21.2	— 18.4	— 17.5	— 10.7	— 15.5
13	— 17.8	— 18.0	— 16.7	— 10.5	— 15.4
14	— 11.2	— 15.9	— 15.9	— 10.4	— 14.5
15	— 17.8	— 15.0	— 14.8	— 10.3	— 13.5
16	— 20.0	— 16.8	— 14.4	— 9.9	— 13.9
17	— 24.3	— 16.8	— 14.1	— 9.7	— 14.0
18	— 30.0	— 18.9	— 14.5	— 9.5	— 15.1
19	— 26.3	— 18.5	— 14.9	— 9.3	— 15.5
20	— 18.2	— 17.4	— 15.1	— 9.3	— 15.0
21	— 33.0	— 16.4	— 14.4	— 9.1	— 14.5
22	— 23.9	— 17.9	— 14.2	— 8.9	— 15.0
23	— 20.6	— 17.7	— 14.4	— 8.9	— 14.8
24	— 19.5	— 16.7	— 14.1	— 8.9	— 14.2
25	— 34.0	— 15.9	— 13.9	— 8.9	— 13.7
26	— 40.3	— 15.8	— 13.5	— 8.7	— 13.9
27	— 36.3	— 20.3	— 13.6	— 8.6	— 14.3
28	— 22.5	— 20.3	— 15.0	— 8.6	— 15.0
Mean	— 26.90	— 20.35	— 16.54	— 9.90	— 16.34

1923 March.

Day	9 a. m.				
	Surf.	0.3 m.	0.8 m.	1.6 m.	0.1 m.
1	— 24.0	— 18.5	— 15.2	— 8.7	— 14.5
2	— 32.0	— 18.1	— 15.0	— 8.8	— 14.5
3	— 28.3	— 17.5	— 14.7	— 8.9	— 14.6
4	— 31.8	— 17.4	— 14.4	— 8.8	— 14.5
5	— 35.3	— 17.4	— 14.3	— 8.8	— 14.7
6	— 30.8	— 20.0	— 14.5	— 8.7	— 15.1
7	— 32.5	— 22.6	— 15.5	— 8.8	— 15.1
8	— 28.4	— 21.0	— 16.2	— 8.9	— 15.3
9	— 28.0	— 19.4	— 16.0	— 9.0	— 15.2
10	— 36.6	— 18.7	— 15.6	— 9.0	— 15.0
11	— 42.0	— 18.4	— 15.0	— 9.0	— 15.4
12	— 39.5	— 18.7	— 15.0	— 9.1	— 15.8
13	— 34.4	— 18.6	— 14.9	— 9.0	— 16.0
14	— 39.4	— 18.5	— 14.8	— 9.0	— 16.1
15	— 38.7	— 18.4	— 14.7	— 8.9	— 16.3
16	— 40.4	— 18.5	— 14.7	— 8.9	— 16.5
17	— 40.0	— 18.7	— 14.8	— 8.9	— 16.7
18	— 35.6	— 18.9	— 14.8	— 8.9	— 16.9
19	— 38.7	— 18.8	— 14.8	— 8.9	— 16.9
20	— 38.6	— 18.8	— 14.8	— 8.9	— 17.0
21	— 32.0	— 18.7	— 14.8	— 8.9	— 17.0
22	— 25.4	— 18.4	— 14.8	— 8.9	— 16.7
23	— 32.2	— 17.8	— 14.5	— 8.9	— 16.3
24	— 32.9	— 17.9	— 14.5	— 8.9	— 16.3
25	— 25.0	— 17.7	— 14.5	— 8.9	— 16.1
26	— 25.5	— 17.2	— 14.3	— 8.9	— 15.6
27	— 20.8	— 16.9	— 14.1	— 8.9	— 15.3
28	— 28.0	— 16.4	— 13.9	— 8.9	— 14.8
29	— 26.3	— 16.4	— 13.9	— 8.9	— 14.8
30	— 22.9	— 16.5	— 13.5	— 8.9	— 15.0
31	— 21.9	— 16.3	— 13.5	— 8.8	— 14.6
Mean	— 31.87	— 18.29	— 14.71	— 8.89	— 15.63

1923 May.

Day	8 a. m.				
	Surf.	0.3 m.	0.8 m.	1.6 m.	0.1 m.
1	-17.0	-11.5	-10.0	-7.2	-10.8
2	-18.8	-11.6	-10.0	-7.1	-10.8
3	-14.0	-11.6	-9.9	-7.0	-10.8
4	-14.3	-11.4	-9.9	-7.0	-10.5
5	(-11.0)	-11.2	-9.8	-6.9	-10.3
6	-15.3	-11.0	-9.6	-6.9	-10.0
7	-13.0	-10.9	-9.5	-6.9	-10.0
8	-13.1	-10.9	-9.5	-6.9	-9.8
9	-11.3	-10.7	-9.4	-6.9	-9.6
10	-8.3	-10.4	-9.3	-6.8	-9.2
11	-12.0	-9.9	-9.0	-6.7	-8.7
12	-14.2	-9.9	-8.9	-6.7	-8.7
13	-11.3	-9.8	-8.8	-6.6	-8.8
14	-11.2	-9.9	-8.8	-6.5	-8.8
15	-11.2	-9.8	-8.7	-6.4	-8.5
16	-10.0	-9.4	-8.6	-6.4	-8.2
17	-9.5	-9.4	-8.5	-6.4	-8.0
18	-12.0	-9.1	-8.3	-6.3	-8.0
19	-12.7	-9.1	-8.3	-6.2	-8.0
20	-10.6	-8.9	-8.0	-6.0	-7.9
21	-8.4	-8.9	-8.0	-6.0	-8.0
22	-13.0	-8.7	-8.0	-5.9	-7.6
23	-12.0	-8.8	-7.9	-5.9	-7.5
24	-10.4	-8.7	-7.9	-5.9	-7.5
25	-10.3	-8.3	-7.8	-5.8	-7.4
26	-10.0	-8.2	-7.6	-5.8	-7.2
27	-4.7	-8.0	-7.5	-5.7	-6.8
28	-3.0	-7.8	-7.4	-5.7	-6.4
29	-4.3	-7.4	-7.2	-5.6	-6.1
30	-3.0	-7.0	-7.0	-5.5	-5.6
31	-3.0	-6.7	-6.8	-5.4	-5.2
Mean	-10.74	-9.51	-8.58	-6.35	-8.41

1923 April.

Day	8 a. m.				
	Surf.	0.3 m.	0.8 m.	1.6 m.	0.1 m.
1	-17.6	-15.7	-13.4	-8.8	-14.2
2	-12.8	-15.1	-13.1	-8.7	-13.5
3	-12.1	-14.3	-12.8	-8.6	-12.9
4	-11.5	-13.9	-12.5	-8.5	-12.2
5	-16.4	-13.4	-12.1	-8.4	-11.7
6	-20.7	-13.2	-11.9	-8.3	-11.6
7	-22.0	-13.1	-11.5	-8.3	-11.9
8	-22.0	-13.0	-11.5	-8.1	-12.1
9	-19.0	-12.9	-11.3	-7.9	-12.2
10	-24.0	-12.9	-11.1	-7.8	-12.1
11	-19.6	-12.9	-11.1	-7.9	-12.3
12	-22.6	-12.9	-11.0	-7.8	-12.3
13	-22.1	-12.9	-11.0	-7.7	-12.2
14	-19.6	-12.9	-11.0	-7.6	-12.4
15	-18.4	-12.8	-10.9	-7.5	-12.2
16	-27.3	-12.6	-10.7	-7.4	-12.1
17	-24.9	-12.7	-10.6	-7.4	-12.2
18	-26.0	-12.7	-10.6	-7.4	-12.5
19	-27.0	-12.9	-10.6	-7.4	-12.6
20	(-28.0)	-12.9	-10.6	-7.4	-12.9
21	-29.3	-12.9	-10.6	-7.4	-13.0
22	-24.1	-12.9	-10.6	-7.3	-12.9
23	-25.8	-12.9	-10.6	-7.3	-12.8
24	-17.3	-12.8	-10.6	-7.3	-12.7
25	-23.8	-12.6	-10.5	-7.3	-12.1
26	-21.4	-12.4	-10.4	-7.3	-12.1
27	-18.3	-12.5	-10.5	-7.4	-12.1
28	-14.4	-12.2	-10.4	-7.3	-11.8
29	-13.0	-11.9	-10.3	-7.3	-11.3
30	-16.4	-11.5	-10.2	-7.2	-10.9
Mean	-20.58	-13.01	-11.13	-7.73	-12.33

1923 June.

Day	8 a. m.				
	Surf.	0.3 m.	0.8 m.	1.6 m.	0.1 m.
1	—4.0	—6.4	—6.6	—5.4	—4.9
2	—4.0	—6.4	—6.4	—5.3	—4.8
3	—4.5	—6.1	—6.2	—5.3	—4.5
4	—	—5.9	—6.0	—5.2	—4.2
5	—	—5.7	—6.0	—5.1	—4.1
6	—	—5.8	—6.0	—5.1	—4.1
7	—	—5.5	—6.0	—5.1	—3.8
8	—	—5.1	—5.7	—5.0	—3.4
9	—	—4.5	—5.3	—5.0	—3.0
10	—	—4.5	—5.0	—4.9	—2.9
11	—	—4.4	—4.9	—4.7	—2.7
12	—	—4.3	—4.9	—4.7	—2.5
13	—	—3.9	—4.6	—4.5	—2.3
14	—	—3.3	—4.5	—4.4	—1.8
15	—	—2.9	—4.5	—4.5	—1.2
16	—	—2.5	—4.4	—4.5	—0.8
17	—	—1.9	—3.8	—4.4	—0.6
18	—	—1.9	—3.5	—4.2	—0.6
19	—	—1.7	—3.4	—4.1	—0.6
20	—	—1.7	—2.8	—4.0	—0.5
21	—	—1.4	—2.7	—3.9	—0.5
22	—	—1.4	—2.6	—3.7	—0.5
23	—	—1.4	—2.8	—3.7	—0.5
24	—	—1.4	—2.6	—3.6	—0.5
25	—	—1.3	—2.6	—3.5	—0.5
26	—	—1.1	—2.4	—3.3	—0.1
27	—	—1.0	—2.3	—3.2	—0.2
28	—	—0.8	—2.2	—3.1	—0.2
29	—	—0.7	—2.2	—3.1	—0.1
30	—	—0.4	—1.9	—3.0	—0.1
Mean		— 3.18	— 4.16	— 4.32	— 1.88

1923 July.

Days	Means of Temperatures during 5 à 6 days at 8 a. m.				
	0.00 m.	0.25 m.	0.75 m.	1.25 m.	2.00 m.
1—5	0.0	—0.4	—1.7	—2.4	—2.6
6—10	0.0	—0.2	—1.3	—2.0	—2.2
11—15	0.0	—0.2	—1.2	—1.7	—1.9
16—20	0.0	0.0	—1.2	—1.5	—1.4
21—25	0.0	0.0	—1.1	—1.4	—1.4
26—31	0.0	0.0	—1.1	—1.4	—1.3
Mean	0.00	—0.13	—1.27	—1.73	—1.80

1923 September.

Day	9 a. m.			
	0.00 m.	0.25 m.	0.70 m.	1.20 m.
1	(- 0.3)	(- 0.4)	(- 0.7)	(- 0.9)
2	(- 0.3)	(- 0.4)	(- 0.7)	(- 0.9)
3	- 0.3	(- 0.4)	(- 0.7)	(- 0.9)
4	- 0.4	(- 0.4)	(- 0.7)	(- 0.9)
5	- 0.4	- 0.5	- 0.8	- 1.0
6	- 1.8	- 0.4	- 0.7	- 0.9
7	- 2.0	- 0.5	- 0.7	- 0.9
8	- 2.0	- 0.5	- 0.7	- 0.9
9	- 3.0	- 0.6	- 0.8	- 1.1
10	- 4.0	- 0.5	- 0.7	- 1.0
11	- 3.2	- 0.6	- 0.7	- 0.9
12	- 4.6	- 0.6	- 0.7	- 1.0
13	- 4.7	- 0.7	- 0.7	- 0.9
14	- 4.2	- 0.7	- 0.7	- 1.0
15	- 4.7	- 0.6	- 0.7	- 1.0
16	- 4.7	- 0.7	- 0.7	- 0.9
17	- 8.2	- 0.6	- 0.6	- 0.9
18	- 7.0	- 0.9	- 0.7	- 1.0
19	- 6.0	- 1.4	- 0.8	- 1.1
20	- 6.8	- 1.7	- 0.8	- 1.2
21	- 4.0	- 1.7	- 0.8	- 1.2
22	- 2.3	- 1.7	- 0.9	- 1.3
23	- 6.3	- 1.9	- 1.1	- 1.3
24	- 4.5	- 2.2	- 1.2	- 1.4
25	- 7.5	- 2.0	- 1.2	- 1.3
26	- 6.5	- 2.6	- 1.2	- 1.4
27	- 7.2	- 2.8	- 1.2	- 1.3
28	- 12.2	- 3.4	- 1.2	- 1.3
29	- 12.0	- 3.6	- 1.1	- 1.3
30	- 10.0	- 4.4	- 1.1	- 1.3
Mean	- 4.70	- 1.31	- 0.84	- 1.08

1923 August.

Days	Means of temperatures during 5 à 6 days at 8 a. m.				
	0.00 m.	0.25 m.	0.75 m.	1.25 m.	2.00 m.
1-5	0.0	0.0	- 1.0	- 1.3	- 1.2
6-10	0.0	0.0	- 0.9	- 1.2	- 1.1
11-15	0.0	0.0	- 0.9	- 1.1	- 1.1
16-20	0.0	0.0	- 0.8	- 1.0	- 1.2
21-25	0.0	0.0	- 0.7	- 0.9	- 1.2
26-31	0.0	0.0	- 0.7	- 0.9	- 1.2
Mean	0.00	0.00	- 0.83	- 1.07	- 1.17

1923 October.

Day	9 a. m.			
	0.00 m.	0.25 m.	0.70 m.	1.20 m.
1	-11.4	-4.6	-1.0	-1.3
2	-6.3	-4.1	-1.1	-1.3
3	-12.0	-3.6	-1.1	-1.3
4	-15.3	-4.3	-1.1	-1.3
5	-6.6	-4.5	-1.0	-1.3
6	-8.4	-4.2	-1.1	-1.3
7	-8.8	-4.0	-1.1	-1.3
8	-10.0	-4.2	-1.2	-1.3
9	-10.2	-4.5	-1.2	-1.3
10	-11.0	-4.9	-1.2	-1.3
11	-9.4	-5.0	-1.3	-1.3
12	-16.2	-5.1	-1.5	-1.3
13	-14.0	-5.9	-1.7	-1.3
14	-9.3	-5.6	-2.0	-1.3
15	-7.5	-4.9	-2.0	-1.3
16	-8.1	-4.9	-2.2	-1.3
17	-6.9	-4.7	-2.2	-1.4
18	-8.2	-4.9	-2.2	-1.4
19	-12.3	-5.2	-2.2	-1.4
20	-10.8	-6.2	-2.4	-1.5
21	-11.2	-6.2	-2.6	-1.5
22	-18.3	-6.9	-2.7	-1.4
23	-14.0	-7.8	-3.0	-1.4
24	-15.6	-8.0	-3.3	-1.6
25	-14.2	-8.3	-3.7	-1.6
26	-15.0	-8.3	-3.8	-1.6
27	-13.0	-8.5	-4.0	-1.7
28	(-14.4)	(-9.2)	(-4.7)	(-2.0)
29	(-15.0)	(-10.0)	(-5.2)	(-2.2)
30	(-18.6)	(-11.0)	(-5.7)	(-2.4)
31	(-17.8)	(-12.0)	(-6.4)	(-2.7)
Mean	-11.93	-6.18	-2.45	-1.50

1923 November.

Day	Noon				
	0.00 m.	0.25 m.	0.75 m.	1.25 m.	2.00 m.
1	(-24.0)	(-12.7)	(-6.4)	(-2.8)	(-1.5)
2	(-19.0)	(-12.6)	(-7.0)	(-3.1)	(-1.5)
3	(-17.8)	(-12.4)	(-7.6)	(-3.4)	(-1.5)
4	(-21.2)	(-13.2)	(-7.8)	(-3.7)	(-1.5)
5	(-20.0)	(-14.0)	(-8.1)	(-4.1)	(-1.5)
6	(-20.3)	(-14.5)	(-8.5)	(-4.4)	(-1.5)
7	(-21.2)	(-14.5)	(-8.9)	(-4.8)	(-1.5)
8	(-17.1)	(-14.0)	(-9.0)	(-5.1)	(-1.5)
9	(-20.0)	(-13.4)	(-9.0)	(-5.4)	(-1.5)
10	-21.5	-14.5	-9.5	-5.9	-1.5
11	-23.5	-16.5	-10.2	-6.1	-1.5
12	-21.2	-17.9	-11.1	-6.3	-1.6
13	-18.9	-15.9	-11.7	-6.9	-1.7
14	-20.0	-16.4	-11.2	-7.2	-2.0
15	-21.8	-16.9	-11.4	-7.0	-2.1
16	-18.8	-16.0	-11.4	-7.2	-2.4
17	-23.8	-16.6	-11.5	-7.5	-2.4
18	-26.8	-19.3	-12.5	-7.8	-2.5
19	-26.8	-20.1	-12.9	-7.9	-2.5
20	-27.7	-20.9	-13.4	-8.5	-2.7
21	-27.3	-21.1	-14.3	-9.0	-2.8
22	-21.8	-19.5	-14.3	-9.0	-2.8
23	-19.5	-18.1	-13.8	-9.1	-2.9
24	-26.4	-19.8	-14.1	-9.3	-3.0
25	-24.8	-19.2	-14.1	-9.5	-3.1
26	-27.7	-20.6	-14.4	-9.7	-3.2
27	-24.5	-20.4	-14.3	-9.5	-3.2
28	-19.8	-18.7	-14.3	-9.6	-3.3
29	-20.7	-17.9	-13.9	-9.7	-3.4
30	-26.0	-18.0	-13.3	-9.4	-3.4
Mean	-22.33	-16.85	-11.33	-6.96	-2.25

1924 January.

Day	Noon				
	0.00 m.	0.25 m.	0.75 m.	1.25 m.	2.00 m.
1	-20.8	(-20.6)	(-18.8)	(-14.2)	(-5.9)
2	-25.2	-21.5	-18.4	-14.4	-5.9
3	-28.3	-22.6	-17.2	-13.3	-5.7
4	-24.1	-23.1	-17.5	-12.8	-5.7
5	-27.3	-21.9	-17.5	-12.8	-5.7
6	-30.0	-23.7	-17.5	-12.9	-5.9
7	-28.5	(-24.6)	(-18.0)	(-13.1)	(-5.9)
8	-30.8	-25.7	-18.7	-13.4	-5.8
9	-29.0	-25.2	-19.5	-13.9	-6.1
10	-29.7	-25.2	-19.2	-13.8	-6.1
11	-27.5	-24.5	-18.9	-13.7	-6.0
12	-29.3	-24.3	-18.7	-13.7	-6.2
13	-29.7	-25.1	-19.0	-13.8	-6.2
14	-28.7	-25.2	-19.9	-14.4	-6.4
15	-28.6	-24.7	-19.1	-14.0	-6.4
16	-28.7	-24.3	-18.7	-13.8	-6.4
17	-27.1	-25.4	-19.7	-14.3	-6.5
18	-22.9	-21.7	-18.1	-13.5	-6.3
19	-25.9	-22.6	-18.6	-14.1	-6.7
20	-28.8	(-23.5)	(-18.8)	(-14.0)	(-6.7)
21	-26.8	-23.2	-18.8	-13.9	-6.8
22	-28.7	-23.9	-18.9	-13.9	-6.8
23	-28.5	-24.9	-19.3	-14.3	-6.9
24	-27.8	-23.7	-18.8	-14.1	-6.9
25	-26.8	-23.8	-19.1	-14.4	-7.0
26	-29.4	-24.8	-19.6	-14.7	-7.1
27	-26.8	-23.7	-19.2	-14.6	-7.1
28	-31.6	(-26.5)	(-19.8)	(-14.8)	(-7.1)
29	-29.8	-25.8	-20.0	-15.1	-7.2
30	-29.5	-24.9	-19.7	-14.9	-7.3
31	-31.2	-25.4	-19.5	-14.6	-7.2
Mean	-27.99	-24.06	-18.85	-13.97	-6.45

1923 December.

Day	Noon				
	0.00 m.	0.25 m.	0.75 m.	1.25 m.	2.00 m.
1	-28.3	-20.1	-13.5	-9.5	-3.5
2	-28.3	-21.0	-14.5	-9.9	-3.5
3	-28.2	-21.0	-14.7	-10.0	-3.7
4	-27.3	(-21.3)	(-15.0)	(-10.2)	(-3.7)
5	-27.9	-21.7	-15.3	-10.4	-3.7
6	-29.7	-22.1	-15.5	-10.5	-3.8
7	-29.5	-23.2	-16.0	-10.6	-3.9
8	-30.1	-23.6	-16.2	-10.9	-4.0
9	-31.2	-24.4	-17.1	-11.3	-4.0
10	-31.2	-24.2	-16.9	-11.0	-4.0
11	-34.4	-25.8	-17.5	-11.6	-4.1
12	-32.7	-25.5	-17.8	-11.7	-4.1
13	-33.3	-26.6	-18.6	-12.4	-4.3
14	-32.8	-26.7	-19.0	-12.6	-4.4
15	-31.5	-26.0	-18.8	-12.6	-4.5
16	-25.7	-24.5	-18.7	-12.8	-4.7
17	-26.6	-23.8	-18.2	-12.8	-4.6
18	-33.2	-24.9	-17.8	-12.8	-4.7
19	-32.8	-26.3	-18.4	-12.7	-4.9
20	-32.6	-25.8	-18.7	-13.0	-4.9
21	-34.4	-27.9	-20.1	-13.7	-5.1
22	-36.1	-28.4	-20.2	-13.6	-5.1
23	-29.8	-27.1	-19.8	-13.4	-5.0
24	-27.0	(-26.5)	(-19.5)	(-13.4)	(-5.1)
25	-30.9	-25.7	-19.1	-13.4	-5.1
26	-24.2	-23.9	-19.3	-13.6	-5.4
27	-26.8	-23.3	-18.9	-13.7	-5.4
28	-27.8	-23.3	-18.3	-13.6	-5.3
29	-29.3	-23.7	-18.3	-13.4	-5.6
30	-26.3	-23.6	-18.6	-13.5	-5.7
31	-26.6	-23.8	-19.2	-13.9	-5.9
Mean	-29.89	-24.38	-17.73	-12.21	-4.57

1924 February.

Day	Noon				
	0.00 m.	0.25 m.	0.75 m.	1.25 m.	2.00 m.
1	-33.7	-27.7	-20.8	-15.4	-7.6
2	-33.9	-27.9	-20.6	-15.4	-7.6
3	-35.0	-29.2	-21.8	-16.1	-7.8
4	-35.1	-29.7	-22.1	-16.3	-7.9
5	-35.3	-30.0	-22.6	-16.4	-7.9
6	-31.7	-27.7	-22.0	-16.3	-8.0
7	-33.5	-28.7	-22.4	-16.5	-8.0
8	-33.7	-28.8	-21.9	-16.1	-8.0
9	-34.3	-29.2	-22.7	-16.8	-8.2
10	-34.3	-30.3	-23.2	-17.1	-8.3
11	(-27.0)	(-26.0)	(-22.4)	(-17.0)	(-8.4)
12	-27.3	-25.2	-21.6	-16.9	-8.4
13	-27.2	-24.5	-20.9	-16.5	-8.5
14	-33.5	-26.5	-21.1	-16.7	-8.6
15	-33.8	-28.6	-22.4	-17.0	-8.9
16	-27.4	-26.2	-21.4	-16.5	-8.8
17	-28.7	-25.4	-21.2	-16.7	-8.9
18	-27.7	-26.1	-21.0	-16.4	-8.8
19	-28.6	-25.1	-20.5	-15.8	-9.1
20	-28.6	-25.2	-20.2	-15.7	-9.0
21	-28.9	-25.6	-20.6	-16.0	-8.9
22	-30.7	-26.4	-20.8	-16.1	-8.9
23	-26.2	-25.0	-20.4	-15.8	-8.7
24	-27.6	-24.3	-20.4	-16.0	-8.8
25	-29.3	-25.7	-20.4	-16.0	-8.9
26	-27.1	-25.0	-20.2	-15.8	-8.8
27	-29.9	-24.9	-20.5	-16.0	-8.9
28	-31.0	-26.6	-20.0	-15.7	-8.9
29	-34.4	-28.5	-21.4	-16.2	-9.1
Mean	-30.88	-26.90	-21.29	-16.25	-8.50

1924 March.

Day	1 p. m.				
	0.00 m.	0.25 m.	0.75 m.	1.25 m.	2.00 m.
1	-33.6	-29.3	-21.9	-16.4	-9.2
2	-33.7	-29.5	-22.0	-16.5	-9.1
3	-34.2	-29.4	-22.4	-16.9	-9.3
4	-35.0	-30.4	-22.9	-17.3	-9.6
5	-28.2	-28.0	-22.9	-17.2	-9.4
6	-26.7	-26.4	-22.6	-17.1	-9.2
7	-25.5	-25.0	-21.9	-17.1	-9.5
8	-28.2	-24.8	-21.1	-17.1	-9.8
9	-28.1	-25.4	-20.8	-16.5	-9.7
10	-26.6	-25.2	-20.6	-16.9	-9.9
11	-28.2	-25.6	-20.2	-16.2	-9.6
12	-29.1	-26.6	-20.6	-16.2	-9.6
13	-28.0	-26.2	-20.9	-16.3	-9.5
14	-27.5	-26.2	-20.8	-16.2	-9.5
15	-27.5	-26.2	-20.9	-16.5	-9.6
16	-28.1	-26.2	-21.1	-16.5	-9.6
17	-28.0	-26.0	-21.1	-16.5	-9.6
18	-29.8	-26.8	-21.3	-16.6	-9.6
19	-27.7	-26.0	-21.0	-16.5	-9.8
20	-25.8	-25.3	-21.0	-16.5	-9.8
21	-26.4	-24.2	-20.9	-16.6	-9.7
22	-28.7	-25.6	-20.8	-16.8	-10.0
23	-27.3	-25.4	-20.4	-16.4	-9.8
24	-27.2	-25.1	-20.1	-16.3	-9.9
25	-24.4	-23.9	-20.3	-16.3	-10.0
26	-25.2	-24.0	-20.1	-16.0	-9.9
27	-25.8	-24.3	-19.9	-15.8	-9.8
28	-25.2	-24.4	-19.9	-15.9	-9.9
29	-25.2	-24.6	-20.2	-16.1	-9.7
30	-24.5	-24.5	-20.1	-16.0	-9.8
31	-23.8	-24.4	-20.1	-16.1	-9.8
Mean	-27.85	-25.96	-20.99	-16.49	-9.65

1924 May.

Day	Noon					
	0.00 m.	0.25 m.	0.75 m.	1.25 m.	2.00 m.	3.00 m.
1	—	—15.7 (—15.5)	—14.8 (—14.4)	—12.9 (—12.6)	—8.7 (—8.6)	—2.1 (—2.1)
2	—	—	—	—	—	—
3	—	—15.2 (—15.2)	—14.0 (—14.0)	—12.3 (—12.3)	—8.6 (—8.6)	—2.1 (—2.1)
4	—	—14.6 (—14.6)	—13.8 (—13.8)	—12.2 (—12.2)	—8.6 (—8.6)	—2.5 (—2.5)
5	—	—14.2 (—14.2)	—13.2 (—13.2)	—11.8 (—11.8)	—8.5 (—8.5)	—2.8 (—2.8)
6	—	—13.4 (—13.4)	—12.7 (—12.7)	—11.5 (—11.5)	—8.5 (—8.5)	—2.8 (—2.8)
7	—	—12.6 (—12.6)	—12.1 (—12.1)	—11.3 (—11.3)	—8.4 (—8.4)	—2.8 (—2.8)
8	—	—11.8 (—11.8)	—11.6 (—11.6)	—11.0 (—11.0)	—8.4 (—8.4)	—2.9 (—2.9)
9	—	—11.0 (—11.0)	—11.1 (—11.1)	—10.8 (—10.8)	—8.4 (—8.4)	—2.9 (—2.9)
10	—	—9.5 (—9.5)	—10.5 (—10.5)	—10.5 (—10.5)	—8.3 (—8.3)	—2.9 (—2.9)
11	—	—9.1 (—9.1)	—10.3 (—10.3)	—10.3 (—10.3)	—8.2 (—8.2)	—3.0 (—3.0)
12	—	—8.7 (—8.7)	—10.0 (—10.0)	—10.0 (—10.0)	—8.0 (—8.0)	—3.0 (—3.0)
13	—	—8.6 (—8.6)	—9.5 (—9.5)	—9.5 (—9.5)	—7.7 (—7.7)	—2.9 (—2.9)
14	—	—8.5 (—8.5)	—9.1 (—9.1)	—9.1 (—9.1)	—7.4 (—7.4)	—2.9 (—2.9)
15	—	—8.0 (—8.0)	—9.0 (—9.0)	—9.0 (—9.0)	—7.5 (—7.5)	—3.1 (—3.1)
16	—	—7.6 (—7.6)	—8.9 (—8.9)	—8.9 (—8.9)	—7.4 (—7.4)	—3.0 (—3.0)
17	—	—7.2 (—7.2)	—8.6 (—8.6)	—8.7 (—8.7)	—7.3 (—7.3)	—3.1 (—3.1)
18	—	—6.8 (—6.8)	—8.4 (—8.4)	—8.5 (—8.5)	—7.1 (—7.1)	—3.1 (—3.1)
19	—	—6.5 (—6.5)	—8.1 (—8.1)	—8.3 (—8.3)	—7.0 (—7.0)	—3.1 (—3.1)
20	—	—6.2 (—6.2)	—7.8 (—7.8)	—8.1 (—8.1)	—6.9 (—6.9)	—3.2 (—3.2)
21	—	—6.0 (—6.0)	—7.6 (—7.6)	—7.9 (—7.9)	—6.8 (—6.8)	—3.2 (—3.2)
22	—	—5.8 (—5.8)	—7.3 (—7.3)	—7.7 (—7.7)	—6.7 (—6.7)	—3.2 (—3.2)
23	—	—5.5 (—5.5)	—7.1 (—7.1)	—7.5 (—7.5)	—6.6 (—6.6)	—3.3 (—3.3)
24	—	—5.3 (—5.3)	—6.8 (—6.8)	—7.3 (—7.3)	—6.5 (—6.5)	—3.3 (—3.3)
25	—	—5.1 (—5.1)	—6.5 (—6.5)	—7.1 (—7.1)	—6.4 (—6.4)	—3.3 (—3.3)
26	—	—4.8 (—4.8)	—6.3 (—6.3)	—6.9 (—6.9)	—6.3 (—6.3)	—3.4 (—3.4)
27	—	—4.6 (—4.6)	—6.0 (—6.0)	—6.7 (—6.7)	—6.2 (—6.2)	—3.4 (—3.4)
28	—	—4.3 (—4.3)	—5.8 (—5.8)	—6.5 (—6.5)	—6.1 (—6.1)	—3.5 (—3.5)
29	—	—4.1 (—4.1)	—5.5 (—5.5)	—6.3 (—6.3)	—6.0 (—6.0)	—3.5 (—3.5)
30	—	—4.3 (—4.3)	—5.4 (—5.4)	—6.2 (—6.2)	—6.0 (—6.0)	—3.6 (—3.6)
31	—	—4.6 (—4.6)	—5.5 (—5.5)	—6.2 (—6.2)	—5.9 (—5.9)	—3.5 (—3.5)
Mean	—	—8.55	—9.28	—9.15	—7.39	—3.02

1924 April.

Day	1 p. m.					
	0.00 m.	0.25 m.	0.75 m.	1.25 m.	2.00 m.	3.00 m.
1	—23.9 (—23.9)	—23.6 (—23.6)	—19.8 (—19.8)	—16.0 (—16.0)	—9.8 (—9.8)	—
2	—23.9 (—23.9)	—23.3 (—23.3)	—19.6 (—19.6)	—15.8 (—15.8)	—9.8 (—9.8)	—
3	—24.0 (—24.0)	—23.3 (—23.3)	—19.5 (—19.5)	—16.1 (—16.1)	—9.8 (—9.8)	—
4	—23.0 (—23.0)	—23.0 (—23.0)	—19.5 (—19.5)	—16.0 (—16.0)	—9.8 (—9.8)	—
5	—22.8 (—22.8)	—22.6 (—22.6)	—19.1 (—19.1)	—15.5 (—15.5)	—9.8 (—9.8)	—
6	—22.1 (—22.1)	—22.0 (—22.0)	—18.7 (—18.7)	—15.4 (—15.4)	—9.8 (—9.8)	—
7	—21.4 (—21.4)	—21.4 (—21.4)	—18.4 (—18.4)	—15.2 (—15.2)	—9.7 (—9.7)	—
8	—21.1 (—21.1)	—21.5 (—21.5)	—18.2 (—18.2)	—15.2 (—15.2)	—9.8 (—9.8)	—
9	—22.3 (—22.3)	—21.8 (—21.8)	—18.1 (—18.1)	—15.0 (—15.0)	—9.7 (—9.7)	—
10	—23.3 (—23.3)	—22.3 (—22.3)	—18.1 (—18.1)	—14.9 (—14.9)	—9.6 (—9.6)	—
11	—21.2 (—21.2)	—21.2 (—21.2)	—18.7 (—18.7)	—15.4 (—15.4)	—9.6 (—9.6)	—
12	—21.0 (—21.0)	—21.7 (—21.7)	—18.4 (—18.4)	—15.1 (—15.1)	—9.5 (—9.5)	—
13	—20.6 (—20.6)	—21.3 (—21.3)	—18.1 (—18.1)	—14.9 (—14.9)	—9.4 (—9.4)	—
14	—19.2 (—19.2)	—20.3 (—20.3)	—17.7 (—17.7)	—14.6 (—14.6)	—9.4 (—9.4)	—
15	—19.0 (—19.0)	—19.5 (—19.5)	—17.4 (—17.4)	—14.6 (—14.6)	—9.4 (—9.4)	—
16	—18.9 (—18.9)	—19.6 (—19.6)	—17.2 (—17.2)	—14.2 (—14.2)	—9.4 (—9.4)	—
17	—17.7 (—17.7)	—19.0 (—19.0)	—16.9 (—16.9)	—14.0 (—14.0)	—9.4 (—9.4)	—
18	—17.1 (—17.1)	—17.8 (—17.8)	—16.5 (—16.5)	—13.8 (—13.8)	—9.3 (—9.3)	—
19	—	—18.6 (—18.6)	—16.1 (—16.1)	—13.7 (—13.7)	—9.3 (—9.3)	—
20	—	—18.8 (—18.8)	—15.9 (—15.9)	—13.6 (—13.6)	—9.3 (—9.3)	—
21	—	—18.6 (—18.6)	—16.1 (—16.1)	—13.6 (—13.6)	—9.3 (—9.3)	—2.1 (—2.1)
22	—	—18.4 (—18.4)	—15.9 (—15.9)	—13.7 (—13.7)	—9.2 (—9.2)	—2.3 (—2.3)
23	—	—18.2 (—18.2)	—15.9 (—15.9)	—13.7 (—13.7)	—9.2 (—9.2)	—2.0 (—2.0)
24	—	—18.4 (—18.4)	—15.8 (—15.8)	—13.5 (—13.5)	—8.9 (—8.9)	—1.8 (—1.8)
25	—	—18.6 (—18.6)	—15.7 (—15.7)	—13.3 (—13.3)	—8.9 (—8.9)	—2.4 (—2.4)
26	—	—18.6 (—18.6)	—15.6 (—15.6)	—13.1 (—13.1)	—8.8 (—8.8)	—2.4 (—2.4)
27	—	—18.4 (—18.4)	—15.5 (—15.5)	—12.9 (—12.9)	—8.9 (—8.9)	—2.4 (—2.4)
28	—	—18.3 (—18.3)	—15.4 (—15.4)	—12.8 (—12.8)	—8.8 (—8.8)	—2.7 (—2.7)
29	—	—16.2 (—16.2)	—15.4 (—15.4)	—13.0 (—13.0)	—8.8 (—8.8)	—2.1 (—2.1)
30	—	—15.7 (—15.7)	—15.1 (—15.1)	—12.9 (—12.9)	—8.8 (—8.8)	—2.6 (—2.6)
Mean	—	—20.07	—17.28	—14.38	—9.37	—

Discussion of results.

In order to obtain the yearly oscillations in temperature at different depths the appended table (Table 17) brings together the averages during the months when the snow-covering above the thermometers was *left undisturbed*. Thus we ignore December 1922—May 1923 because the snow above the thermometers was occasionally removed during the first part of that period (see p. 33). The remaining months give us a smaller amount of material, it is true, but that material is all the better defined.

The monthly averages for October 1922 have been obtained from the temperatures for the period October 1—31¹⁾ after a mean temperature had been assigned to the first nine days of the month, viz. -10° for 0 m., -7° for 0.3 m., -2.8° for 0.8 m. and -1.2° for 1.6 m. The values obtained are consequently somewhat uncertain, but assuredly better than the monthly averages that are obtained solely from the temperatures for the last 21 days.

The monthly averages for October and November 1922 and for June, September and October 1923, which refer to other depths in the above tables, have been reduced in the following table to the depths 0.25 m., 0.75 m., 1.25 m., and 2.00 m., by the use of graphic interpolation. The mean values for the depths observed during a certain month have been set out in a system of co-ordinates with the depths as ordinates and the temperatures as abscissas, after which a curve has been drawn closely following the points indicated. From this curve the temperatures at the depths desired have then been determined. The same method has been employed to determine the mean temperatures at the surface of the ice during June 1923 and April and May 1924, which was effected by the graphic extrapolation of the corresponding monthly curves.

Table 17.

Mean	0.00 m.	0.25 m.	0.75 m.	1.25 m.	2.00 m.	Remarks
January24	— 28.0	— 24.1	— 18.9	— 14.0	— 6.5	} Means of two years
February24	— 30.9	— 26.9	— 21.3	— 16.3	— 8.5	
March24	— 29.1	— 26.0	— 21.0	— 16.5	— 9.6	
April24	— 21.6	— 20.1	— 17.3	— 14.4	— 9.4	
May24	— 7.4	— 8.6	— 9.3	— 9.2	— 7.4	
June23	— 1.5	— 3.0	— 4.1	— 4.5	— 3.8	
July23	— 0.0	— 0.1	— 1.3	— 1.7	— 1.8	
August23	— 0.0	— 0.0	— 0.8	— 1.1	— 1.2	
September23	— 4.7	— 1.3	— 0.9	— 1.1	— 1.3	
October22, 23	— 12.3	— 7.6	— 3.3	— 1.6	— 1.4	
November 22, 23	— 23.0	— 17.8	— 11.9	— 7.1	— 2.4	
December23	— 29.9	— 24.4	— 17.7	— 12.2	— 4.6	
Mean	— 15.70	— 13.32	— 10.65	— 8.31	— 4.82	

The temperatures, as a rule, are the averages of a single month's observations. Only October and November each comprise values for two months. The temperatures during each of these four months were as follows:

¹⁾ The date October 11, 1922 has been omitted owing to the change of date made after the passage of the 180th meridian.

		0.00 m.	0.25 m.	0.75 m.	1.25 m.	2.00 m.
October	22	— 12.6	— 9.0	— 4.4	— 1.8	— 1.4
October	23	— 11.9	— 6.2	— 2.2	— 1.5	— 1.4
November	22	— 23.7	— 18.7	— 12.6	— 7.2	— 2.4
November	23	— 22.3	— 16.8	— 11.3	— 7.0	— 2.3

The annual periods of the temperature at the different depths have been computed from the monthly averages in Table 17. The formula which I have used is:

$$t_m = M + a \sin (A + m)$$

t_m being the mean temperature for the month, M the mean annual temperature, a the amplitude, A the phase-angle and m the angle representing the month, reckoned from the middle of January. The result of the computation of the annual period for the depth 0.00, 0.25, 0.75, 1.25, and 2.00 meters is shown in Table 18, the curves themselves in Fig. 7.

Table 18.

Depth	0.00 m.	0.25 m.	0.75 m.	1.25 m.	2.00 m.
M	— 15.70°	— 13.32°	— 10.65°	— 8.31°	— 4.82°
a	16.82°	14.60°	11.17°	8.36°	4.40°
A	259.6°	250.9°	240.9°	230.7°	210.4°
January	— 32.2	— 27.1	— 20.4	— 14.8	— 7.0
February	— 31.5	— 27.6	— 21.8	— 16.6	— 8.6
March	— 26.6	— 24.4	— 20.2	— 16.1	— 9.2
April	— 18.7	— 18.1	— 16.1	— 13.6	— 8.6
May	— 10.0	— 10.6	— 10.5	— 9.7	— 7.0
June	— 2.9	— 3.8	— 4.9	— 5.4	— 4.8
July	+ 0.8	+ 0.5	— 0.9	— 1.8	— 2.6
August	+ 0.1	+ 1.0	+ 0.5	— 0.1	— 1.0
September	— 4.8	— 2.3	— 1.1	— 0.5	— 0.4
October	— 12.7	— 8.5	— 5.2	— 3.0	— 1.0
November	— 21.4	— 16.1	— 10.8	— 7.0	— 2.6
December	— 28.5	— 22.9	— 16.4	— 11.3	— 4.8
Min.	— 32.7°	— 28.1°	— 21.9°	— 16.8°	— 9.3°
Max.	January 26 + 1.3°	February 3 + 1.4°	February 14 + 0.6°	February 24 + 0.1°	March 17 — 0.4°
Mean error	July 30 ± 1.55°	August 7 ± 1.40°	August 18 ± 1.02°	August 28 ± 0.64°	September 17 ± 0.46°

Table 18 gives only *monthly* averages of the temperature. In order to obtain the daily temperatures we must for every depth study new sine functions with an amplitude that is $\frac{\pi}{12} : \sin \frac{\pi}{12} = 1.0115$ times bigger than a ¹⁾. It is from these new functions that the extreme temperatures in Table 18 have been computed.

During the months of July and August the harmonic analysis gives positive temperatures at several depths, while the observed ice-temperatures of course do not exceed 0°. Also otherwise it appears as though the accordance of the observed values to a simple sinus function were less good. That we under such circumstances represent our temperature values at different depths by a simple sinus-oscillation is due to the fact that we wish to compare our values with those of the "Fram"-Expedition, whose temperatures were expressed in this way. The "Fram"-Expedition's ice-temperatures are found in Table 19.

¹⁾ Hann-Süring, Lehrbuch der Meteorologie, Leipzig 1915, p. 774.

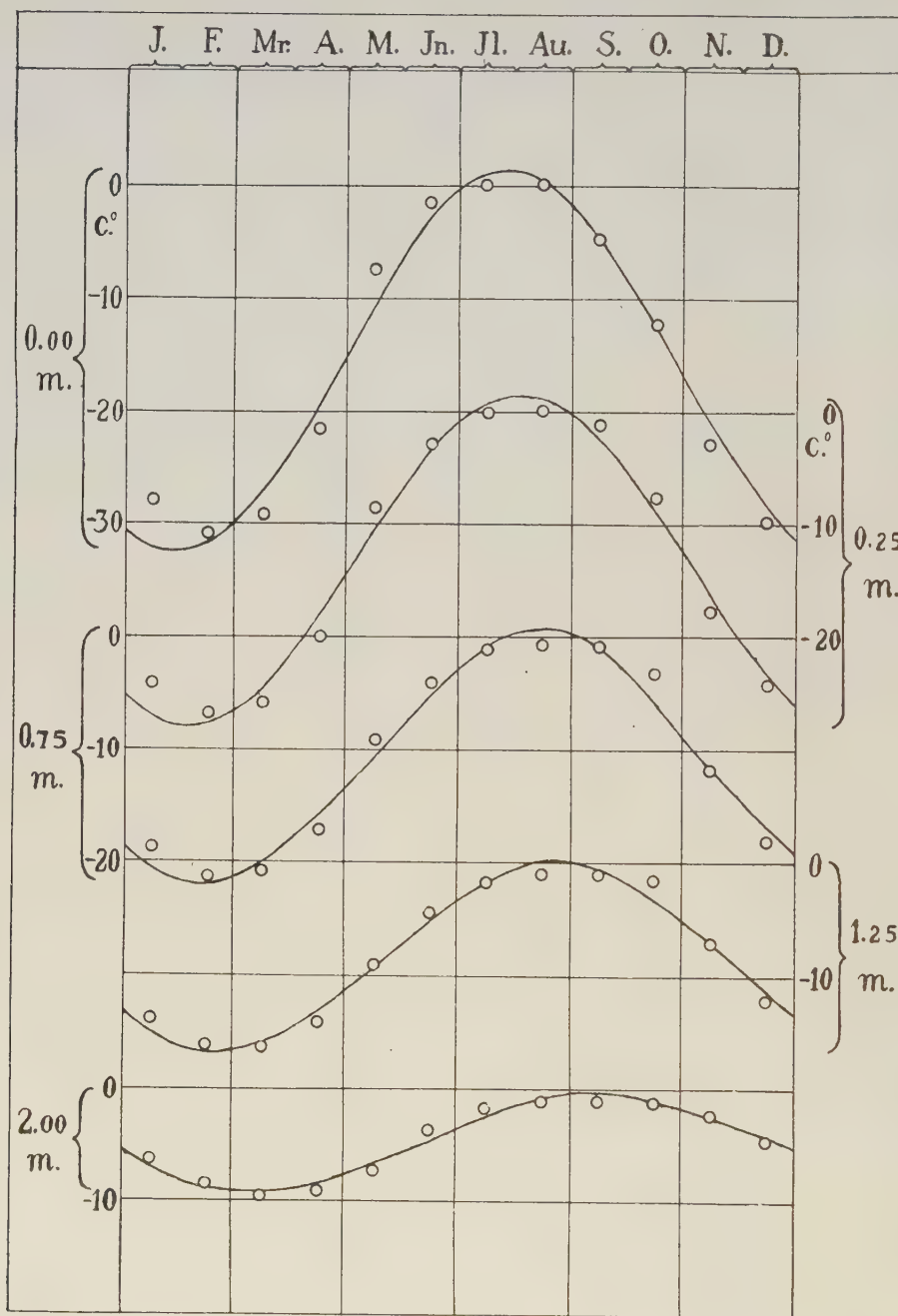


Fig. 7. Annual variation of temperature of sea-ice in different depths, represented by monthly mean values and computed curves.

Table 19.

Depth	0.4 m.	0.8 m.	1.2 m.	1.6 m.	2.0 m.
<i>M</i>	— 12.2°	— 10.1°	— 8.5°	— 7.0°	— 6.0°
<i>a</i>	12.05°	10.0°	8.45°	6.7°	5.8°
<i>A</i>	255.9°	249.3°	243.1°	236.7°	232.9°
January.....	— 23.9	— 19.5	— 16.1	— 12.6	— 10.6
February.....	— 23.8	— 20.0	— 17.0	— 13.6	— 11.7
March.....	— 20.5	— 17.9	— 15.6	— 12.4	— 11.3
April.....	— 15.1	— 13.7	— 12.3	— 10.6	— 9.9
May.....	— 8.9	— 8.5	— 8.0	— 7.8	— 6.7
June.....	— 3.6	— 3.8	— 3.9	— 4.0	— 3.7
July.....	— 0.5	— 0.7	— 1.0	— 1.4	— 1.4
August.....	— 0.6	— 0.2	— 0.05	— 0.3	— 0.2
September.....	— 3.9	— 2.3	— 1.4	— 1.5	— 0.6
October.....	— 9.3	— 6.6	— 4.7	— 3.3	— 2.0
November.....	— 15.5	— 11.7	— 9.0	— 6.1	— 5.3
December.....	— 20.8	— 16.5	— 13.1	— 10.0	— 8.2
Min. {	— 24.4°	— 20.2°	— 17.0°	— 13.8°	— 11.9°
	January 29	February 5	February 11	February 17	February 31
Max. {	— 0.0°	— 0.0°	+ 0.05°	— 0.2°	— 0.1°
	August 2	August 9	August 15	August 21	August 25

If we compare the yearly mean temperatures (*M*) in Table 18 with those of Table 19, we find that these values at great depths are higher with us than the corresponding values during the "Fram"-Expedition. The conditions are shown best by Fig. 8, which brings out the variations of the mean temperature with depth during the two expeditions. At a depth of 2 m., for instance, we found a mean temperature of — 4.8° against — 6.0° during the "Fram" Expedition. The difference is

probably explained by the fact that *the values of the "Fram"-Expedition are too low*, on account of imperfectness in the measuring method itself. The "Fram"-Expedition used for measuring very slow thermometers, which were fastened to rods, and lowered into narrow holes which were bored in the ice. When after a lapse of several hours, the thermometers were thought to have assumed the ice-temperature at a certain depth, they were pulled up quickly and read. The risk, by in this way using a hole in the ice for temperature readings, is that during the winter, cold air can run down into

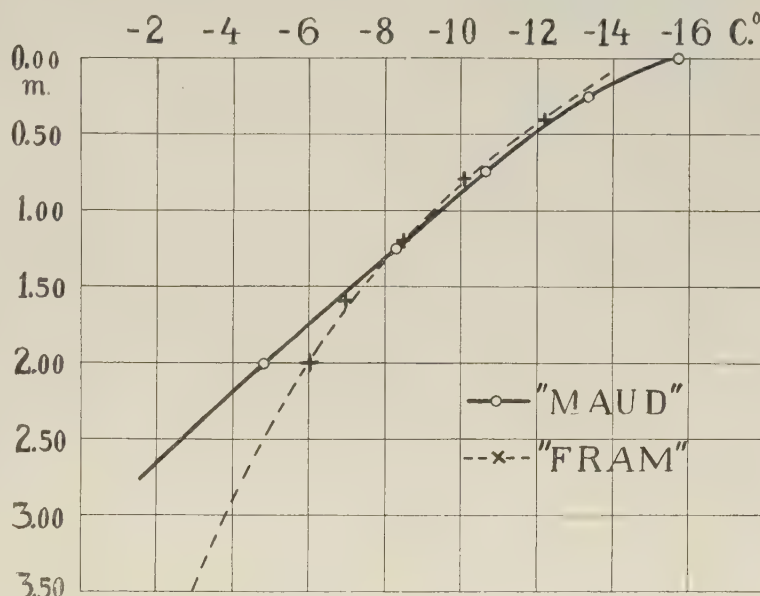


Fig. 8. Annual mean temperature of sea-ice in different depths according to observations from the "Maud"- and "Fram"-Expeditions.

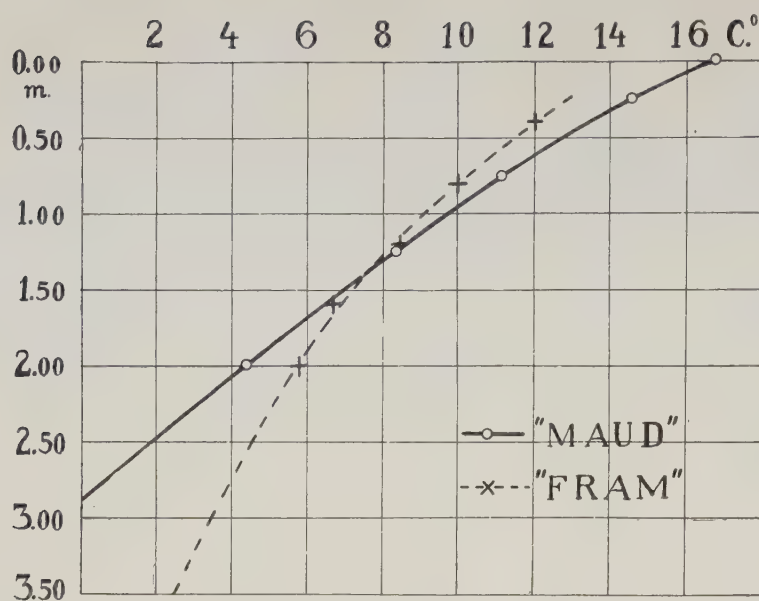


Fig. 9. Annual amplitude of temperature of sea-ice in different depths according to observations from the "Maud"- and "Fram"-Expeditions.

the hole from above, in spite of every precaution being taken. Already Nansen himself feared that such cold air in penetrating down could lower the observed ice-temperatures at great depths, and if one studies "Fram's" ice-temperatures, one finds that his anticipations have come true. "Fram's" winter temperatures at great depths are too low. As the summer temperatures on the contrary are not subject to the same source of errors, but appear to be normal,

the abnormal low winter temperatures account for the fact that the yearly amplitudes become too large. On account of this at 2.00 m. during the "Fram"-Expedition a is 5.8° compared to 4.4° for the "Maud"-Expedition.

It deserves to be mentioned that if the curve from the "Maud"-Expedition in Fig. 8 is extrapolated the mean temperature will be -1.6° at 2.8 meters' depth, while the corresponding curve from the "Fram"-Expedition, if extrapolated gives -1.6° not before at a depth of 4.5 m. Similar results are obtained if the amplitudes of both expeditions are set out graphically (Fig. 9). If the curve from the "Maud"-Expedition is extrapolated, it gives an amplitude of 0.0 at 2.9 m. depth, while the "Fram" curve if extrapolated does not give 0.0 before at a depth of 5.5 m. These extrapolations form a good criterion on the correctness of the temperature measurements, because if the values are correct one must get the temperature -1.6 and the amplitude 0.0 at the depth which corresponds to the average thickness of the ice. The temperature of the sea-water at a few meters' depth has in fact a constant value of -1.6° all the year round. Regarding the "Maud"-Expedition, the average ice-thickness calculated from M and a , agree very well with the probable ice thickness, (see p. 37). while on the other hand the curves of the "Fram"-Expedition -- if they are correct -- would correspond to an ice thickness more than twice the thickness of that which Nansen had assumed. Thus, it is probable that the method used on the "Fram"-Expedition for measuring ice temperatures has given partly wrong values, while our measurements with electrical thermometers seem to give quite satisfactory results. We can therefore with entire confidence use these ice-temperatures for the further calculations of conductivity and heat-transport which will be put forth in the next chapter.

VI. Thermal Conductivity of Ice.

Previous investigations. Methods of determinations.

The thermal conductivity of sea-ice (k) has been previously investigated by J. Stefan,¹⁾ who computed k from the thickness of the ice which had been formed after a certain time (z). It is presumed that the temperature conditions during the process of freezing were known. But the formula worked out by Stefan *holds good only in the case that the new-formed ice has no salinity*. In his argument, in fact, Stefan assumes a specific heat in ice c which is independent of the temperature and a heat of fusion λ which is also fixed. Now it is true that this is justified in the matter of fresh-water ice; but in the case of ice containing salt, the conditions are quite otherwise, inasmuch as c in this latter case varies extremely with the temperature and there is no longer any such thing as heat of fusion.

This involves, as has been said, that Stefan's formula is valid only in case the new-formed ice is completely free of salt. If that is the case we have.

$$h^2 \left(1 + \frac{\tau}{3\lambda}\right) = \frac{2k \cdot z \cdot t}{\lambda \cdot \sigma}$$

where (h) is the thickness of the ice in centimeters λ and σ the melting heat and the density respectively of the ice, t the mean difference during the period z between the temperature of the air and the freezing point of the ice, and finally τ is the temperature at the surface of the ice at the end of the period z .

At the end of the yearly period of freezing during the winter $\tau = 0$, and the expression is simplified into

$$h^2 = \frac{2k \cdot z \cdot t}{\lambda \cdot \sigma} = A \cdot z \cdot t$$

where A is a constant and equals $\frac{2k}{\lambda \cdot \sigma}$

From the measurements of thickness taken by numerous British expeditions to the American Arctic Archipelago 1829—1853²⁾ Stefan has calculated that A in the average, can be put at 1.17×10^{-4} , if z is expressed in seconds. From this we get

$k = \frac{0.000117 \lambda \cdot \sigma}{2}$ which, as $\sigma = 0.92$ and $\lambda = 80$ gives $k = 4.3 \times 10^{-3}$. But

this value of k is far from trustworthy, inasmuch as the ice between the Canadian islands is probably sufficiently full of salt to make it no longer justifiable to use Stefan's formula.

When it is a question of computing the thermometric conductivity of sea-ice ($K = k : \rho \cdot c$) from the yearly variations of the ice-temperature at different depths we can not as has been done by Mohn³⁾ make use of the formula that Fourier worked out for the propagation of heat in a homogeneous medium. This formula applies to a medium of infinite thickness while the thickness of the ice, in fact, is small in comparison to the thickness of the layer of ice which—if it existed—would be subjected to yearly variations of temperature. Under the layer of ice there is the sea-water, which throughout the year has a temperature practically of -1.6° . Hence the

¹⁾ Sitzungsber. Kais. Akad. d. Wiss. Wien 1890, Bd. 98, 2 a, p. 965.

²⁾ A Complete list of these measurements is given in Ann. d. Hydr. 1881. p. 1.

³⁾ The Norwegian North Polar Expedition etc.

yearly amplitude of the temperature at the under-surface of the ice—which for the sake of simplicity is assumed always to lie at the same depth—must also be 0° , and in order that this may be the case the original oscillation must here be compensated by another harmonic oscillation, which starts from the water. This implies that the original oscillation, which from the surface of the ice penetrates down into the ice and which in the usual way diminishes its amplitude and changes its phase as it penetrates deeper down, meets at the under-surface of the ice with another oscillation with equally large amplitude but with a difference of phase amounting to 180° in relation to the former. This oscillation continues upwards with the same logarithmic decrement and change of phase as the original one. By adding these two oscillations we obtain the observed harmonic oscillation at the different depths. The conditions are best illustrated by Fig. 10. The original—fictive—oscillation of temperature is here denoted

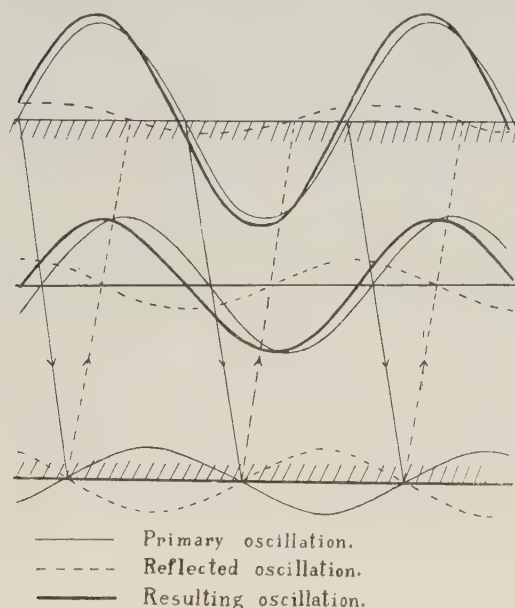


Fig. 10. Schematical representation of the annual oscillation of temperature in a layer of limited thickness.

by a thin continuous line, that which starts from the sea-water by a dotted line, and the true oscillation, which is the resultant of the two preceding ones, by a thick continuous line.

There is no great difficulty in following mathematically the conditions that are represented in Fig. 10 and, with the help of formulae, computing K and later k from the actually observed yearly course of the temperature at the different depths. The reason why we do not enter into anything of the kind is the fact that even these modified Fourier formulae would give us an untrustworthy value for k . Above we have assumed, first that the thickness of the ice is constant all the year round, and secondly that the heat-conductivity is the same at different depths. Neither of these assumptions, however, holds good in nature. It is known to everybody that during the greater

part of the year the ice is constantly growing, and owing to the dissimilarities in structure of different layers of ice (the upper layers always show more air-bubbles than the lower ones) it is probable that K is not constant but a function of the depth.

The only possibility of computing k from the series of temperatures consists in measuring the temperature gradients at different depths and observing their changes with time. Suppose that somewhere in an extensive piece of sea-ice we take a cylinder with a vertical axis and horizontal end surfaces, the latter measuring 1 cm.^2 and that we observe the amount of heat which during t seconds passes the different surfaces of the cylinder. Owing to the great horizontal extent of the ice, no heat passes through the curved surface of the cylinder: in other words the current of heat is always at right angles to the surface of the ice. If during the period t we call the mean gradient G_1 at the upper surface and G_2 at the lower, and the corresponding conductivities k_1 and k_2 then during the time t the quantity of heat that has passed through the upper surface is $k_1 \cdot G_1 \cdot t$ and that which has passed through the lower surface is $k_2 \cdot G_2 \cdot t$. If it should happen that after the period t the cylinder has the same heat content as before, we have,

$$k_1 \cdot G_1 \cdot t = k_2 \cdot G_2 \cdot t \text{ or } k_1 \cdot G_1 = k_2 \cdot G_2$$

If, on the other hand, the mean temperature of the cylinder has changed from τ_1 to τ_2 , we obtain the following expression, in which h denotes the height of the cylinder, c the average specific heat of the whole cylinder between τ_1 and τ_2 and σ its mean specific gravity:

$$k_1 \cdot G_1 \cdot t - k_2 \cdot G_2 \cdot t = h \cdot c \cdot \sigma (\tau_1 - \tau_2)$$

Now if we calculate the mean gradient at the two depths that correspond to the position of the upper and lower surface of the cylinder first during a period at the end of which the mean temperature of the cylinder has returned to its original value, and secondly during a period during which the difference in temperature between the beginning and the end is as large as possible, we can compute k_1 and k_2 . If the mean gradients in the first case are G'_1 and G'_2 and in the second case G''_1 and G''_2 , and if the length of the period and the difference in temperature in the second period are denoted by t'' and $(\tau_1'' - \tau_2'')$, we obtain the following equation

$$k_1 \cdot G'_1 = k_2 \cdot G'_2$$

$$\text{and } k_1 \cdot G''_1 \cdot t'' - k_2 \cdot G''_2 \cdot t'' = h \cdot c \cdot \sigma (\tau_1'' - \tau_2'')$$

from which k_1 and k_2 can be computed if h , c , σ , t'' , τ_1'' and τ_2'' are known.

A computation of the conductivity of the sea-ice according to the above scheme has been worked out both for the ice whose temperatures were measured during the period from October 1922 to August 1923 and for the ice which was used in the observations extending from November 1923 to May 1924.

The period October 1922—August 1923.

The heat conductivity was determined at the bounding surfaces at the layers of 0.00—0.25 m. and 0.50—1.25 m.

(a) 0.00—0.25 m. In this computation use could be made only of the months October and November 1922, during which the ice was bare and the "surface temperature" consequently meant the temperature at 0.00 m. (see p. 33). The salinity in the layer was 0.0 ‰, which involved a $c=0.50$ at all temperatures; the specific gravity was 0.89.

The mean temperature in this layer on December 1 at 8 p. m. was -22.6° . The same temperature had earlier prevailed in this layer on November 12 at 7 p. m. The mean gradients during the whole period, computed direct from the temperatures of the ice were 0.164 C./cm. between 0.00 and 0.30 m., 0.125 C./cm. between 0.30 and 0.80 m., and 0.108 C./cm. between 0.80 and 1.60 m. If these mean gradients are set out as rectangles in a system of co-ordinates, and if a gradient curve be drawn in close connection to these rectangles we obtain a gradient of 0.191 C./cm. at 0.00 m., and of 0.148 C./cm. at 0.25 m. If we call the conductivity at 0.00 m. $k_{0.00}$ and that at 0.25 m. $k_{0.25}$, we obtain the following:

$$0.191 k_{0.00} = 0.148 k_{0.25} \text{ or } k_{0.00} = 0.775 k_{0.25}.$$

The mean temperature in the layer on October 13 at 8 p. m. was -8.1° , the temperature being obtained by striking an average of the temperature in the layer on October 13 and October 14 at 8 a. m. Later the temperature in the layer at the same time of day came to the following amounts: on October 25 $= -16.7^\circ$, on November 1 $= -9.7^\circ$, and on November 24 $= -25.6^\circ$. The mean gradients in the layers 0.00—0.30 m., 0.30—0.80 m., and 0.80—1.60 m. and the gradients graphically computed from these at 0.00 m. and 0.25 m. for the periods October 14—25, October 26—November 1 and November 2—24 are given below:

Period 1922	Number of days	Mean gradients at the depths			Gradients		Start temp.—end temp.	$k_{0.00} \times 10^3$	$k_{0.25} \times 10^3$
		0.00—0.30	0.30—0.80	0.80—1.60	0.00 m.	0.25 m.			
October 14—25.	12	0.165	0.082	0.031	0.209	0.135	+ 8.6	2.6	3.4
October 26 —									
November 1....	6	0.113	0.110	0.064	0.091	0.123	— 7.0	2.2	2.9
November 2—24	23	0.206	0.123	0.092	0.259	0.172	+ 15.9	2.4	3.1

The table also gives the difference between the starting and the final temperature of the layer and the values determined for each period of $k_{0.00}$ and $k_{0.25}$. The latter are worked out with the help of the formulae on p. 57. By way of example we will perform a computation of $k_{0.00}$ and $k_{0.25}$ from the period October 14—25. In the formula

$$k_1 \cdot G_1'' \cdot t'' - k_2 \cdot G_2'' \cdot t'' = h \cdot c \cdot \sigma (t_1'' - t_2'')$$

is $k_1 = k_{0.00} = 0.775$, $k_2 = k_{0.25}$, $G_1'' = 0.209$ C°/cm., $G_2'' = 0.135$ C°/cm., $t'' = 12 \times 24 \times 60 \times 60$ seconds, $h = 25$ cm., $c = 0.50$, $\sigma = 0.89$ and $(t_1'' - t_2'') = 8.6^\circ$. If these values be inserted in the equation, we get

$12 \times 24 \times 60 \times 60 k_{0.25} (0.775 \times 0.209 - 0.135) = 0.5 \times 0.89 \times 25 \times 8.6$, from which $k_{0.25} = 3.4 \times 10^{-3}$, and $k_{0.00} = 2.6 \times 10^{-3}$.

As mean value for the three periods we get

$$k_{0.00} = 2.4 \times 10^{-3} \text{ and } k_{0.25} = 3.1 \times 10^{-3}.$$

(b) 0.50—1.25 m. The specific gravity was 0.91. The salinity in the layer was 1.5 ‰, which implied that the mean value of c was 0.59, between -3.3° and -19.1° and 0.57 between -4.4° and -19.1° . The layer had the same temperature on November 1, 1922 at 8 p. m. and on May 31, 1923 at 8 p. m. (-6.5°). The gradients at 0.50 and 1.25 m. during this period were 0.079 and 0.075 C°/cm. respectively. These were calculated from the mean gradients during the same period for the layers 0.30—0.80 m., 0.80—1.60 m., and 1.60—2.85 m.¹⁾, which amounted to 0.079, 0.075 and 0.049 C°/cm. respectively. If the conductivity at 0.50 m. is called $k_{0.50}$ and that at 1.25 m. is called $k_{1.25}$, we thus have

$$0.079 k_{0.50} = 0.075 k_{1.25} \text{ or } k_{0.50} = 0.950 k_{1.25}.$$

The temperature in this layer sank from -3.3° (at 8 p. m. on October 13, 1922) to -19.1° (at 8 p. m. on January 25, 1923) and then rose again to -4.4° (at 8 p. m. on June 15). The heat-conductivity was determined both during the period of falling temperature and during that of rising temperature. The mean gradients, the gradients etc. during the two periods are given in the table below. The mean values for both determinations were:

$$k_{0.50} = 4.0 \times 10^{-3} \text{ and } k_{1.25} = 4.2 \times 10^{-3} \text{ C.}^\circ \text{ cm.}$$

¹⁾ The approximate mean depth during the period. At that depth the temperature was assumed to be -1.5° .

Period 1922 — 1923	Number of days	Mean gradients at the depth			Gradients		Start temp.— end temp.	$k_{0.50} \times 10^3$	$k_{1.25} \times 10^3$
		0.30—0.80	0.80—1.60	1.60 — underside of ice	0.50 m.	1.25 m.			
October 14 — January [25..	103	0.111 ₄	0.090 ₁	0.041	0.112 ₀	0.089 ₀	+ 15.8°	3.9	4.1
January 26 — June 15.....	141	0.046 ₉	0.053 ₀	0.046	0.045 ₅	0.054 ₀	— 14.7°	4.1	4.3

The period November 1923—May 1924.

The conductivity of this ice was computed according to a slightly different scheme from that which had been previously used, owing to the fact that this year the gradients were better known, and consequently it was worth while to effect the computation of k according to a method which, though more troublesome, was more correct from a mathematical point of view. The mean gradients in the upper and lower surface of the layer were computed for every month—or part of the month—throughout the whole period. Let us call the gradients at the upper and the lower surface during the different months $G'_1, G'_2, \dots$ respectively and $G''_1, G''_2, \dots$ respectively. During the period at the beginning and end of which the temperature in the layer was the same, we then get, if $n_1, n_2, \dots$ represent the number of days in the month

$$k_1 \sum n_i \cdot G'_i = k_2 \sum n_i \cdot G''_i \text{ or } k_1 = \frac{k_2 \sum n_i \cdot G''_i}{\sum n_i \cdot G'_i};$$

The amount of heat which in the course of a month is conveyed to the layer is $(k_1 \cdot G'_i - k_2 \cdot G''_i) \cdot n_i \cdot 24 \times 60 \times 60$. This amount is equal to $\Delta \tau_i \cdot c \cdot \sigma \cdot h$, if $\Delta \tau_i$ denotes the difference, also calculated for each month, between the mean temperature of the layer at the beginning and the end of the month. But as $k_1 = \frac{k_2 \sum n_i \cdot G''_i}{\sum n_i \cdot G'_i}$ we have

$$k_2 = \frac{\Delta \tau_i}{\left(G'_i \frac{\sum n_i \cdot G''_i}{\sum n_i \cdot G'_i} - G''_i \right) n_i} \cdot C$$

where $C (= c \cdot \sigma \cdot h : 86400)$ is practically constant. (The differences which, owing to differences in the temperature, may occur in c and thus also in C are small and play no part in comparison with the great variations which may occur in the fraction in front of C . Hence for all months within the period we can assume a constant mean value for C).

According to the above, we obtain for each month an equation which permits a computation of k_2 . If the magnitudes $\Delta \tau_i$ be called a_i and $\left(G'_i \frac{\sum n_i \cdot G''_i}{\sum n_i \cdot G'_i} - G''_i \right) \cdot n_i$ be called b_i , we get altogether i equations $k_2 = \frac{a_i}{b_i} \cdot C$. If the mean value of k_2 be obtained according to the method of least squares, we get $k_2 = \frac{\sum a_i^2}{\sum a_i \cdot b_i} \cdot C$ because the incidental errors mainly occur in the magnitudes b_i . (The magnitudes a_i are merely differences between the layer temperatures at two different observations and can

therefore be regarded as approximately correct. The magnitudes b_i , on the other hand, depend on the gradient-curves constructed from the mean gradients in the layers 0.00—0.25 m., 0.25—0.75 m. and so on. The way in which these curves are drawn is to some extent subjective, as it is always possible to draw several curves, slightly differing among themselves, but all satisfying the conditions laid down). The conductivity was determined in accordance with the above scheme in four different layers, namely 0.00—0.25 m., 0.25—0.75 m., 0.75—1.25 m. and 0.25—1.25 m. The results can be summarized in the following little table:

Table 20.

Layer	Heat conductivity multiplied by 10^3 at the depth			
	0.00 m.	0.25 m.	0.75 m.	1.25 m.
0.00—0.25 m.	1.7	2.8	—	—
0.25—0.75 m.	—	3.3	4.1	—
0.75—1.25 m.	—	—	4.8	4.9
0.25—1.25 m.	—	3.9	—	5.0
Mean	1.7	3.3	4.5	5.0

In case anyone is interested in following the computation of k_1 and k_2 in the different layers, the following data are appended.

0.00—0.25 m. The salinity was 0.0 ‰, the specific gravity was 0.89, and the specific heat was 0.50. At midnight on 30 November and at 3 a. m. on 1 January the temperature was the same (-22.5°). The gradients at 0.00 m. and 0.25 m. during this period were 0.276 and 0.168 respectively, which makes $k_{0.00} = 0.609 k_{0.25}$. The other magnitudes are given in the appended table:

Month	1 $G_{0.00} \cdot n$	2 $G_{0.25} \cdot n$	3 $G_{0.00} \cdot n \cdot 0.609$	Difference 3—2	$\Delta \tau$
November (20 days)	5.10	2.82	3.11	+ 0.29	+ 4.0
December	8.65	5.27	5.27	0.00	+ 0.4
January	6.45	3.72	3.93	+ 0.21	+ 6.3
February	6.20	3.71	3.78	+ 0.07	+ 2.1
March	4.96	3.35	3.02	— 0.33	— 6.7

0.25—0.75 m. The specific gravity was 0.89. The salinity was 0.4 ‰, which at the temperatures that occurred during the different monthly periods corresponded to a mean specific heat of 0.50. The investigation extended from midnight on November 10 to noon May 7. The temperature at the beginning and end of the period was -12.3° . As we see below,

$$\frac{\sum G_{0.25} \cdot n_i}{\sum G_{0.75} \cdot n_i} = \frac{20.56}{16.31}, \text{ which makes } k_{0.25} = 0.793 k_{0.75}$$

See also the appended table:

Month	1 $G_{0.25} \cdot n$	2 $G_{0.75} \cdot n$	3 $G_{0.25} \cdot n \cdot 0.793$	Difference 3-2	$\Delta \tau$
November (20 days)	2.82	1.98	2.24	+ 0.26	+ 3.6
December.....	5.27	3.63	4.18	+ 0.55	+ 4.8
January.....	3.72	3.04	2.95	- 0.09	+ 2.45
February.....	3.71	2.97	2.94	- 0.03	+ 1.9
March.....	3.35	2.85	2.66	- 0.19	- 3.05
April.....	1.65	1.68	1.31	- 0.37	- 6.55
May (6.5 days).....	0.04	0.16	0.03	- 0.13	- 3.15

0.75—1.25 *m*. The specific gravity was 0.90. The salinity was 1.45 ‰ which, at the temperatures that prevailed during the different monthly periods, corresponded to a mean specific heat of 0.53. The investigation extended from midnight on 10 November to noon on 20 May. The temperature at the beginning and end of this period was —7.9°. As we see below was

$$\frac{\sum G_{0.45} \cdot n_i}{\sum G_{1.25} \cdot n_i} = \frac{16.17}{15.93} \text{ which makes } k_{0.75} = 0.985 k_{1.25}$$

See also the appended table:

Month	1. $G_{0.75} \cdot n$	2. $G_{1.25} \cdot n$	3. $G_{0.75} \cdot n \cdot 0.985$	Difference 3-2	$\Delta \tau$
November (20 days)	1.98	1.70	1.95	+ 0.25	+ 3.5
December.....	3.63	3.26	3.58	+ 0.32	+ 5.2
January.....	3.04	3.04	3.00	- 0.04	+ 1.0
February.....	2.97	2.94	2.93	- 0.01	+ 1.3
March.....	2.85	2.76	2.81	+ 0.05	- 0.9
April.....	1.68	1.83	1.66	- 0.17	- 4.0
May (20 days).....	0.02	0.40	0.02	- 0.38	- 6.1

0.25—1.25 *m*. The specific gravity was 0.89, the salinity was 0.90 ‰ and the specific heat was 0.51. The period lasted from midnight on 10 November to midnight on 10 May. The temperature at the beginning and end was —10.1°.

$$\frac{G_{0.25} \cdot n_i}{G_{1.25} \cdot n_i} \text{ was } = \frac{20.51}{15.83}, \text{ from which we get } k_{0.25} = 0.772 \cdot k_{1.25}$$

See also the appended table:

Month	1. $G_{0.25} \cdot n$	2. $G_{1.25} \cdot n$	3. $G_{0.25} \cdot n \cdot 0.772$	Difference 3-2	$\Delta \tau$
November (20 days)	2.82	1.70	2.18	+ 0.48	+ 3.5
December.....	5.27	3.26	4.07	+ 0.81	+ 5.0
January.....	3.72	3.04	2.87	- 0.17	+ 1.8
February.....	3.71	2.94	2.86	- 0.08	+ 1.6
March.....	3.35	2.76	2.59	- 0.17	- 2.0
April.....	1.65	1.83	1.27	- 0.56	- 5.3
May (10 days).....	- 0.01	0.30	- 0.01	- 0.31	- 4.6

Other Determinations of the Conductivity.

Besides these computations there was also undertaken a determination of k for the layer 0.25—1.25 m. with the help of the directly measured gradients at the depth of 0.25 m. and 1.25 m. (See p. 38). The period lasted from 10 November to 23 December 1923 and yielded a k -value which agreed very closely with the mean values previously found ($k_{0.25} = 3.6 \times 10^{-3}$, and $k_{1.25} = 4.7 \times 10^{-3}$). In this computation, however, the same relation $k_{0.25} = 0.772 k_{1.25}$, was used as in the preceding determination — the period during which the gradients were read direct was too short to permit of a good determination of the relation $k_{0.25} : k_{1.25}$ — and consequently these values have not been taken into account in forming the mean figures.

In the course of the expedition I also made a direct determination of the conductivity of the ice in accordance with a method, of which Fig. 11 gives a schematic idea.

Let us imagine a very long horizontal wire AB , sunk in the ice. Through AB an electric current can be passed at will from a storage battery C ; the strength of the current (i) in the wire is measured by an ampère meter, D . At a short distance a from AB there is a thermocouple whose junctions have a relative distance of Δa .

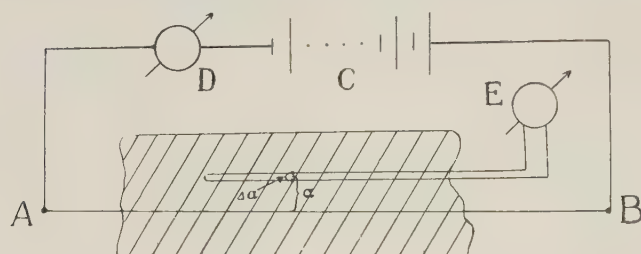


Fig. 11. Arrangement for experimental determinations of heat-conductivity of sea-ice.

The thermocouple and its two junctions lie in the same horizontal plane as AB , and the junctions are so arranged that the connecting line between them intersects AB at a right angle. (In the figure the thermocouple and its junctions have, for the sake of clearness, been drawn on the same vertical plane as AB). A sensitive galvanometer

E is coupled to the thermal circuit. If the current is now admitted through AB for t seconds, every centimeter of the wire receives a certain amount of heat, which amount is known if we know the resistance of the wire and the strength of the current. Let us call the amount of heat per cm. A . After a long time this amount of heat will have completely passed through the cylinder whose axis is AB and whose radius is a . Through each square centimeter of this cylinder there will then have passed an amount

of heat equal to $\frac{A}{2\pi \cdot a}$ but this amount of heat is $= k \int_{t_0}^{\infty} G_a dt$, if the current in the

wire AB is admitted at the time t_0 and if k and G_a are, as before, the heat-conductivity and the gradient respectively. We thus have

$$k = \frac{A}{2\pi \cdot a \int_{t_0}^{\infty} G_a \cdot dt};$$

From this expression k can be computed, for the value of the integral can be obtained by reading at short intervals of time the strength of the current in the thermal circuit, which is proportional to G_a and then setting out G_a as a function of the

time in a sytem of co-ordinates. The readings of the strength of the current are continued till no current passes any longer through the thermal circuit. The surface between the curve that represents G_a and the line $G_a = 0$ will then be equal to the intergral in question.

In the experiments the resistance wire AB and the thermocouple with its connecting wires were fixed in their right relation to one another by stretching them between the ribs of a four-sided wooden frame which was afterwards sunk down through a hole in the ice and was allowed to get frozen in at a depth of 35 cm. The connections both to the resistance wire and to the thermocouple were then led through cables to the laboratory on board the ship, where the strength of the current in both circuits was read off. The thermal current was determined by the aid of a Deprez-d'Arsonval galvanometer with telescope reading. The galvanometer was from the Swedish firm of Rose, and was of the type which is used for radiation measurements. In this combination it gave a deflection of one division for a temperature difference of $0^{\circ}.00768$. The strength of the other current was determined by a sensitive ampèremeter from the Weston Electrical Company, U. S. A.

Only one series of determinations of k was carried out on this method, and here it was found that the heat-conducting capacity for a piece of new ice was 5.1×10^{-3} .

The numerical values in one of the determinations are given below, a was 1.57 cm. and $\Delta a = 0.24$ cm. The current was admitted to AB for 120 seconds. The total amount of heat which in that time passed through 1 cm.² at the place where the thermocouple was situated was 0.193 calories. The mean deviation of the galvanometer during the whole period that the thermal current gave a measurable deviation (20 min.) was 0.99 divisions = 0.0076° . Thus

the corresponding mean gradient was $\frac{0.0076}{0.24} = 0.0317$ C°/cm. and the integral is $0.0317 \times 1200 = 38.0$, and $k = 5.1 \times 10^{-3}$.

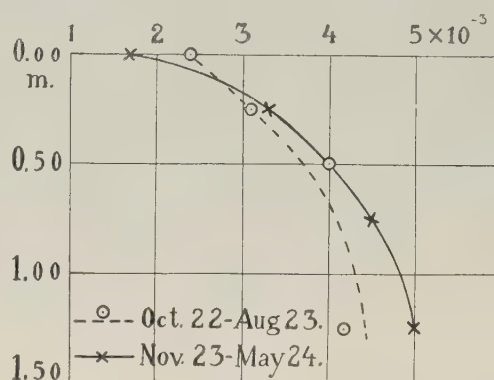


Fig. 12. Heat-conductivity of sea-ice in different depths, derived from observed temperatures in the winters 1922—23 and 1923—24.

Results of conductivity determinations.

If the mean value of the heat-conductivity be set out as a function of the depth we get for the years 1922—1923 and 1923—1924 the curves that have been drawn in Fig. 12. The most striking feature of these curves is the rapid diminution of k that takes place when we approach the surface of the ice from below. This circumstance is assuredly connected with the structure of the ice: at 0.00 m. the ice is full of numerous small air bubbles, a fact which also finds expression in a low specific gravity (about 0.88). At greater depths k seems to tend towards a limiting-value of 5.0×10^{-3} , which also is the heat-conductivity of clean fresh-water ice without bubbles.

VII. Conclusions regarding heat transport to the air from below.

After the previous determinations of the constants of sea-ice we have now possibility of investigating how much heat is conveyed to the air or the ice surface from below. Doing this we only use the temperature measurements from June 1, 1923 to May 31, 1924.

First we will investigate how much heat (Q) which in the course of a whole year, from summer to summer, is supplied *from the sea-water* to an air column with a base-area equal to 1 cm.² The quantity (in gram cal.) is at every ice depth equal to the product of the heat conductivity and the mean gradient, both at the given depth, multiplied by the number of seconds during a whole year. This depends on the fact that in the course of a year the same amount of heat passes all levels in the ice and is conveyed to the air regardless of whether the ice is covered with snow in the meantime, provided that the temperatures of the ice at all levels assume the same values in the second summer as in the first.

The series of the temperatures from the "Maud"-Expedition does not satisfy the strict conditions which are required in order that the calculation of the supply of heat in the air from the sea-water shall be completely correct, inasmuch as the temperature of the ice at the beginning and the end of the period (June 1 and May 31 respectively) differs by about 1°. Moreover, as has been previously pointed out, the temperatures are not quite homogeneous. But these factors play but a small part in comparison with the great variations in the transmission of heat which are assuredly shown by different ice-floes and which are due to differences in the thickness of the ice and above all to dissimilarities in the thickness of the snow covering the ice in the winter—a factor which exerts a great influence on the magnitude of the gradients. It is highly probable, however, that the below value of the aggregate amount of heat conveyed to the air from the water by an area of 1 cm.² of ice in the course of a year, comes very near to a good average value, because the spot where the ice-thermometers were placed seemed to be representative in the matter of snow-conditions. To be on the safe side, however, we should like to regard the value of Q obtained below as doubtful within the limits of 20 %.

In order to calculate Q we have computed the gradients for the depths for which we have determined the conductivity. The needed gradients were obtained by first deriving from the yearly mean temperatures the *mean gradients* during the year for intervals of 0.00—0.25 m., 0.25—0.75 m. and so on. These mean gradients were set out in a system of co-ordinates as rectangles with the depth interval as base and the magnitude of the gradient as height. A continuous curve was then drawn by making the average length of the ordinates in a depth interval (e. g. 0.00—0.25 m.) as great as the height of the corresponding rectangle. From this curve, which represents the variation of the temperature gradient with the depth, the mean gradients in Table 21 have been determined.

Table 21.

Depth (m.)	0.00	0.25	0.75	1.25	2.00
Heat-conductivity (cm. ² , sec. - 1).	1.7×10^{-3}	3.3×10^{-3}	4.5×10^{-3}	5.0×10^{-3}	5.0×10^{-3}
Temp. gradient (C.°, cm. - 1)....	0.107	0.067	0.048	0.047	0.046
Q (gram calories).....	5700	7000	6800	7400	7300

The values of the heat-conductivity in this table are entered from Table 20 p. 60. The products of the first two lines in Table 21 multiplied by $60 \times 60 \times 24 \times 365$ represent the total amounts of heat passing the different levels in one year. These values should agree, as already pointed out, and the discrepancies are not greater than could be expected considering the uncertainty with which the quantities entering in the computation are known. The mean value is

$$Q = 6800 \text{ gr. cal./cm.}^2$$

This represents the amount of heat that the air every year gets from the sea-water. We will immediately see that the amount of heat, received during the cold season by the air from the ice is *bigger*, and so it must be, because during May and June heat is conducted downwards and Q is the algebraic sum of both quantities. During July and August the air loses very much heat in melting ice, but no heat passes down into the ice and adds heat to the sea-water, the gradient in the uppermost layers during these months being equal to zero.

In addition to this calculation of the magnitude of the yearly heat current from the sea-water we will also consider the amounts of heat which during every month of the colder seasons are transmitted to the surface from below. For this purpose we shall first compute the monthly heat-current through one square-cm. in a depth of 0.75 m. We select this level because the heat-conductivity is better known here than in the higher levels. The values for 0.00 and 0.25 m., in fact, suffer from uncertainties owing to the rapid variations in temperature in the 0.00—0.25 m. layer, one effect of which is that a single reading of the temperature per day is really insufficient for the formation of mean gradients. The amounts of heat passing through the 0.75 m. level are

$$24 \times 60 \times 60 \times 4.5 \times 10^{-3} \cdot n_i \cdot G_{i0.75} = 389 \cdot n_i \cdot G_{i0.75} \text{ gr. cal.}$$

where n_i is the number of days in the month i .

The amounts of heat which interest us, however, are those which in the course of each month are transmitted to the upper surface of the ice. But these amounts of heat are the same as those which in the course of the month pass through the 0.75 m. level, if only we add a correction which depends on the difference in the mean temperature of the 0.00—0.75 m. layer between the beginning and the end of the month. If this difference is $\Delta\tau$, and if the specific heat and the specific gravity of the layer are denoted, as before by c and σ , we get, if we call the yield of heat during the month W_i

$$W_i = 389 n_i \cdot G_{i0.75} + 75 \cdot \Delta\tau \cdot c \cdot \sigma = 389 n_i \cdot G_{i0.75} + 34.4 \cdot \Delta\tau.$$

Table 22 gives the values that W assumes during the different months. For September and October — for which months the data refer to another piece of ice — the same value for k (4.5×10^{-3}) has been used as in the other cases.

Table 22.

Month	$G_{0.75} \cdot n$	$\Delta\tau$	W gr. cal./cm. ²	L m.	M C°
September ¹⁾ 1923 ...	— 0.03	3.4	110	300	0.4
October	1.33	7.2	770	190	4.2
November	2.88	7.0	1360	140	10.5
December	3.63	3.3	1530	140	11.4
January 1924	3.04	3.8	1310	140	9.8
February	2.97	1.9	1220	140	10.1
March	2.85	— 5.9	910	150	6.4
April	1.68	— 5.7	460	200	2.5

¹⁾ During the month of September and October the ice is giving off a good deal of latent heat to the air by the freezing of fresh water (pools etc.) on the surface of the ice. This amount of heat is not included in the table as it is not accompanied by changes in temperature or gradients.

From this table we see that a very considerable quantity of heat is conveyed to the air from below during the colder months. The total supply (R) in fact, is 7670 gr.—cal./cm.² or 76700 kg.—cal./m.²

This is the amount of heat which is able to melt 96 cm. of ice. By way of comparison it may be mentioned that the total change in heat content in the Mediterranean from the warmest to the coldest season, according to Aimé's measurements, amounts to 676000 kg.—cal./m.², an amount of heat which is thus about nine times as large.¹⁾

The effect of the heat conducted from below (R) on the temperature is very great, however, owing to special conditions that prevail in the atmosphere above the Polar Ocean. Heat is conveyed to the atmosphere during the period September—April. During these months the Polar Sea is constantly covered by a thin layer of cold air which is scarcely 150 meters deep on the average.²⁾ This layer mixes very little with the layer of air above it; and the consequence of this is that the heat which is conveyed to the air from below mainly benefits that lower layer. Now an amount of heat equal to 0.3077 kg.—cal. is required to raise the temperature of 1 cubic meter of air by one degree. The amount of heat which is given off per day on the average during the period September—April is $\frac{76700}{242}$ kg.—cal. = 317 kg.—cal. This quantity would be sufficient to raise the temperature of the atmosphere in the lowest 150 meters by 6°.9 in one day. This figure is an average for the whole winter. During certain months the supply of heat from below and the corresponding fictiv temperature raising per day may be considerably greater. The second last column in Table 22 contains smoothed values for the thickness of the cold layer (L) as communicated in a letter from Professor Sverdrup. The last figures in the table show how many degrees (M) the temperature of an air column (L) will be raised by a quantity of heat equal to the amount $W: n$ passing the surface of the ice in one day.

The great acquisition of heat by the atmosphere above the Polar Sea during the winter via the ice from the warm water of the sea greatly contributes to diminish the cold of winter and explains the fact that, despite the clear winter sky and the calm weather, we have over the Polar Sea considerably milder winter temperatures than further south over the continent of Asia.

¹⁾ Krümmel: Handbuch der Ozeanographie, Band I, Stuttgart 1907 p. 497.

²⁾ H. U. Sverdrup: The North—Polar cover of cold air. Monthly Weather Review, Washington 1926, p. 53.

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